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MODELLING OF THE FEED-PELLET COOLING PROCESS

presented by

Joao Domingos Biagi

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Agricultural Engineering

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Major professor

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MODELLING OF THE FEED-PELLET COOLING PROCESS

By

Joao Domingos Biagi

A DISSERTATION

**Submitted to
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ABSTRACT

MODELLING OF THE FEED-PELLET COOLING PROCESS

By

Joao Domingos Biagi

The commercial feed industry ranks among the top 25 industries in the United States. It is projected that 107.5 million metric tons of feed will be pelleted in the U.S. in 1985-86.

Pelleting is a process of conditioning, compacting, and extruding small feed particles into larger particles. Following the pelleting process, cooling and drying of the pellets are necessary to remove excess heat and moisture resulting from steam conditioning and frictional heating.

Thin-layer drying of individual pellets was investigated. Experimental drying tests were conducted at 15.6 to 43.3 C, 40 to 70% relative humidity, and 18.1 to 19.1% DB initial moisture content. The thin-layer data was used to determine the equilibrium moisture content equation and diffusion coefficient equation of pelleted feed with a pellet diameter of 4.76 mm and density of 673 kg/m³.

Joao Domingos Biagi

The horizontal-belt cooling of pellets was evaluated experimentally and theoretically in the same temperature, relative humidity, and moisture content range. Two deep-bed simulation models were developed and tested; both models are solvable on PC-size microcomputers. The simulated results are in good agreement with the experimental data.

The effect of the cooling conditions, including the cooling air temperature, humidity and velocity, on the pellet temperature and moisture content in a horizontal-belt pellet cooler was analysed. The cooling air temperature and velocity have a marked effect on both these values; the relative humidity only has an effect on the pellet moisture content.

Likewise, the effect of several pellet properties, including the pellet diameter, conductivity, and specific heat, on the pellet temperature and moisture in a horizontal-belt pellet cooler bed was investigated. The pellet diameter and specific heat are the main pellet properties affecting the cooling rate and drying behavior of a horizontal-belt pellet cooler.

Approved F.D. Becker - Pena
Major Professor 11/14/87

Approved Donald P. Edwards
Department Chairman

Dedicated

to my parents

Domingos and Alcinda

and to my wife

Cintia

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LIST OF SYMBOLS

A	constant
a	constant
B	constant
b	constant
C	specific heat, J/kg K
c	constant
D	diffusion coefficient, m^2/h
DB	dry basis
Di	pellet diameter, m
Dm	pellet dry matter, kg
Dr	pellet radial increment, m
Dt	time increment, h
Dx	cooler depth increment, m
dp	pellet density, kg/m^3
EMC	equilibrium moisture content, decimal, dry basis
G	dry weight flow rate, $\text{kg}/\text{h m}^2$
H	humidity ratio, decimal
h	convective heat transfer coefficient, $\text{W}/\text{m}^2 \text{ K}$
hd	mass transfer coefficient, m/h
h _{fg}	latent heat of vaporization for water in product kJ/kg
i	index
j	index
k	thermal conductivity, W/m K
M	local pellet moisture content, decimal, dry basis
$\bar{M}$	average pellet moisture content, decimal, dry basis
P	mean relative deviation modulus, dimensionless
R	pellet radius, m
RH	relative humidity, decimal
Re	Reynolds number = $(G D_i/\mu)$, dimensionless
r	pellet radial coordinate, m
SA	pellets specific surface area, m^2/m^3
Sc	Schmidt number = $(\mu/D_i dp)$, dimensionless
T	air temperature, C
T _{abs}	absolute temperature, K
t	time, h
x	bed coordinate, m
WB	wet basis

Subscripts

a	air
abs	absolute
e	equilibrium
f	final
o	initial
p	pellet
s	surface
t	time
t+Dt	time plus time increment
v	water vapor
w	water liquid

Greek

π	3.141592654
θ	local pellet temperature, C
$\bar{\theta}$	average pellet temperature, C
α	thermal diffusivity, $\text{W m}^2/\text{J}$
ϵ	bed porosity, decimal
μ	viscosity, kg/h m

1 - INTRODUCTION

Feed pelleting can be defined as the agglomeration of small feed particles into larger pellets by means of a mechanical process in combination with moisture, heat and pressure. The nature of the feed pelleting process requires the removal of excess heat and moisture resulting from steam conditioning and frictional heat during the pelleting phase. This is most economically accomplished by drawing atmospheric air through a uniform bed of pellets, evaporating the excess moisture and at the same time reducing the temperature. Cooling and drying in this manner can be accomplished in a wide range of temperatures and relative humidities without requiring artificial conditioning of the cooling air.

The pelleting process has a relatively short history, beginning in 1929 with the conception and design of equipment using the die- and -roller principle (Robinson, 1977). For many years, pelleting was classified as an art, because the process was governed more by feeling than by the use of instrumentation and controls (Falk, 1985). More recently, the feed industry has become a science due to technology being developed in this field.

The commercial feed industry in the U.S., which ranks among the top 25 industries, currently is composed of about 400 companies, with about 3,000 primary feed manufacturing plants serving 10,000 secondary manufacturing plants (Anderson, 1985).

The formula feed industry is divided by the United States Department of Agriculture in the following categories:

(1) Feed-milling - usually a stationary mill operation at a single location together with a mobile mill based at that location.

(2) Primary feed manufacturing - the processing and mixing of individual feed ingredients, sometimes with addition of a premix at a rate less than 100 pounds/ton of finished feed.

(3) Secondary feed manufacturing - the processing and mixing of one or more ingredients with formula feed supplements. Supplements are usually used at a rate of 300 pounds or more per ton of finished feed, depending on the protein content of the supplement and percentage of protein desired in the finished feed.

(4) Custom grinding and mixing - grinding customer-owned feed ingredients and usually mixing supplements with them. Mainly, this is a service provided to farmers feeding their own animals.

Feed costs represent 60% to 80% of the total production cost of livestock production (Olentine, 1985). It is essential for the livestock or poultry producer to

maximize the use of the feed. To accomplish this, feed is pelleted to prevent spillage and waste, to enhance consumption, and to improve the feed efficiency and the handling characteristics. It is estimated that approximately 90% to 95% of the feed produced in Holland and 65% in the United States is pelleted (Olentine, 1985; Perry, 1984).

There are a number of models presently available for the classification of the status of a nation's economy. Most divide the world into developed and developing countries. Developing usually connotes the fact that a country has not reached the economic development of western industrialized countries. Whatever the status of a developing nation, one of the key areas of growth that is evaluated is the upgrading of agriculture, in particular of the livestock and poultry industries, and thus also the feed industry.

The importance of developing countries in agriculture is shown in Table 1.1. In 1970 the share of the total agriculture output was 64% for the developed countries and 36% for the developing countries. It is projected that in the year 2000 the developing nations will produce 62% of the total agricultural output, while the developed countries will produce 38% (Olentine, 1985). Feed production will follow the same trend.

The problems incurred by feed manufactures vary from country to country. Culture and religion, governmental policies, transportation, handling and storage are among the factors that need to be evaluated when the feed formula industries are analyzed.

Table 1.1 - Production Share of Different Agricultural Sectors in Developed and Developing Countries.

	1970 (%)	2000 (%)
Share of total agriculture output		
Developed	64	38
Developing	36	62
Grain consumption		
Developed	45	33
Developing	55	67
Animal Products		
Developed	64	42
Developing	36	58
From Olentine (1985)		

With the rapid rise in the speed of transportation and the methods of communications, the feed industry has become a world business. The ingredient prices are being determined by world demand rather than local or regional demand as has been the case in the past.

South America, including Brazil (the author's birth place), increased between 1972 and 1982 the per capita food production and increased its share of global exports by 16% (Samuelson, 1988). The feed industry increased accordingly.

Table 1.2 shows the world production and consumption of feed grains. The U.S. share of the world production of feed grains has decreased from 32% in 1981 to a projected 29.5% in 1986, while the U.S. consumption has remained at about 22% since 1981 (Feedstuffs, 1985).

**Table 1.2 - World Production and Consumption of Feed Grains
(corn, barley, soybeans, oats, rye, and millet).**

Country or Region	1981-82	1982-83	1983-84	1985-86 Projected
Production millions of metric tons.				
Canada	26.0	26.5	21.0	21.9
Eastern Europe	64.5	71.8	67.1	74.3
US	246.6	250.7	137.1	237.1
USSR	72.0	86.0	99.0	86.0
Western Europe	87.8	93.6	84.8	103.4
Total Non US	522.1	528.0	548.0	565.7
World Total	768.8	778.8	685.1	802.9
Consumption				
US	154.8	167.9	147.9	165.5
USSR	98.5	98.3	110.5	112.0
World Total	738.6	753.0	758.7	782.7
End of Stocks				
Total Non US	44.7	41.3	33.4	39.4
US	68.2	97.5	31.7	45.8
World Total	113.0	138.7	65.8	85.2
From Feedstuffs (1985)				

Brazil is a developing country with a steady increase in agricultural production in the past ten years. It needs new technologies to support its growth. The pellet cooling techniques, described in this study, should aid in the development of a successful feed pellet manufacturing industry in Brazil.

The effective cooling of the pellets immediately after leaving the pellet-mill is very important; it has a considerable effect on the quality of the pelleted feed. It is essential that the moisture content is controlled to ensure acceptable shelf-life and reduce the risk of mould. Since the cooling and drying in the feed pelleting process have not been investigated in depth (Trickett, 1982), a comprehensive study of these two subjects from a engineering point of view will contribute to a better understanding of the pelleting process.

2 - OBJECTIVES

The main objective of this study is to analyze the cooling and drying of pellets in a horizontal-belt pellet cooler. An experimental investigation had to be conducted of single-layer drying and stationary deep-bed cooling of pellets to verify the simulation models of the horizontal-belt cooling process.

The specific objectives of this investigation of the cooling of feed pellets in a horizontal-belt cooler are:

1. To determine the drying and cooling rate of a single-layer of pellets under various environmental conditions.

2. To determine the equilibrium moisture content and diffusion coefficient of feed pellets under various environmental conditions.

3. To determine the drying and cooling rate of a stationary deep-bed of pellets under various environmental conditions.

4. To develop two microcomputer-based simulation models for the cooling and drying of a horizontal-belt pellet cooler.

5. To investigate the effects of air velocity, air temperature, and air relative humidity on the pellet cooling and drying rate of a horizontal-belt pellet cooler.

6. To investigate the sensitivity of several pellet and bed parameters on the pellet cooling and drying rate of a horizontal-belt pellet cooler.

3 - LITERATURE REVIEW

The literature review will focus on the factors that affect the cooling process of pellets, and on the development of a computer model of the cooling of pellets in a deep-bed cooler. The review is subdivided in eight major sections: (1) feed mills, (2) pelleting process, (3) cooling of pellets, (4) single particle drying equations, (5) pellet properties, (6) quality of pellets, (7) deep-bed models and simulation, and (8) statistics.

3.1 - Feed Mills

The term "feed processing" refers to any treatment that a feedstuff or part of a feedstuff undergoes prior to the consumption by animals. The processing may be one step or a series of steps, and may include cooking, mechanical extraction, dehydration, grinding, and pelleting.

According to Robinson (1971) and Perry (1984), in the United States approximately 60% of the non-forage feeds are processed in feed mills.

A feed mill process flow diagram is shown in Figure 3.1, illustrating the different mill processes and the flow of material from plant entry to exit (Balding, 1985). The receiving is the first process of the plant and includes the actual receiving of the materials, scheduling of ingredients, quality control analysis and material handling. The second process is the processing which consists of the grinding, rolling and flaking operations, and the movement of the materials to and from the processing equipment. The third is the mixing process, including the movement of both sacked and bulk ingredients from storage to the mixing center, proportioning these ingredients, and mixing, conveying, scalping, and blending them. The fourth is the pelleting process which includes conditioning, compacting, extruding, and cooling/drying. The final two processes are packaging, consisting of weighing, bagging, and loading of the finished, packaged products on railcars and trucks. A list of the equipment in a typical feed mill is given in Figure 3.1.

Table 3.1 lists the connected horsepower values for the various processes of a 10-20 ton/h capacity feed manufacturing plant. The processing and pelleting processes account for 70% of the total horsepower required in a feed mill plant.

NOMENCLATURE

Item Number

1. Truck Scale and Hydraulic Dumper
2. Truck Dump Hopper
3. Truck Dump Hopper Conveyor
4. Rail Car Unloading Hopper
5. Rail Car Unloading Conveyor
6. Unloading Conveyors
7. Magnet
8. Bucket Elevator
9. High Level Bin Fill Control
10. Surge Bin
11. Automatic Receiving Scale
12. Feeder Conveyor
13. Scalper / Cleaner
14. Bucket Elevator
15. Horizontal Conveyor
16. Conveyor
17. Outside Grain Storage Bins, 4
18. Conveyor
19. Surge Bin
20. Hammermill
21. Conveyor
22. Bucket Elevator
23. Turnhead Distributor
24. Ingredient Bins, 21
25. Feeder Screws
26. Scale Hopper
27. Automatic Control Panel and Scale
28. 3-Ton Mixer with Surge Bin
29. Mixer Conveyor
30. Bucket Elevator
31. Turnhead Distributor
32. Pellet Mash Bins, 2
33. Pellet Mill
34. Pellet Cooler
35. Crumbler
36. Cooler Fan
37. Cooler Cyclone
38. Pellet Conveyor
39. Pellet Elevator
40. Grader, Pellets and Crumbles
41. Conveyor
42. Turnhead Distributor
43. Bulk Bins, 12
44. Bulk Loadout Hopper and Scale
45. Pellet Fines Return
46. Liquid (Fat) Tanks

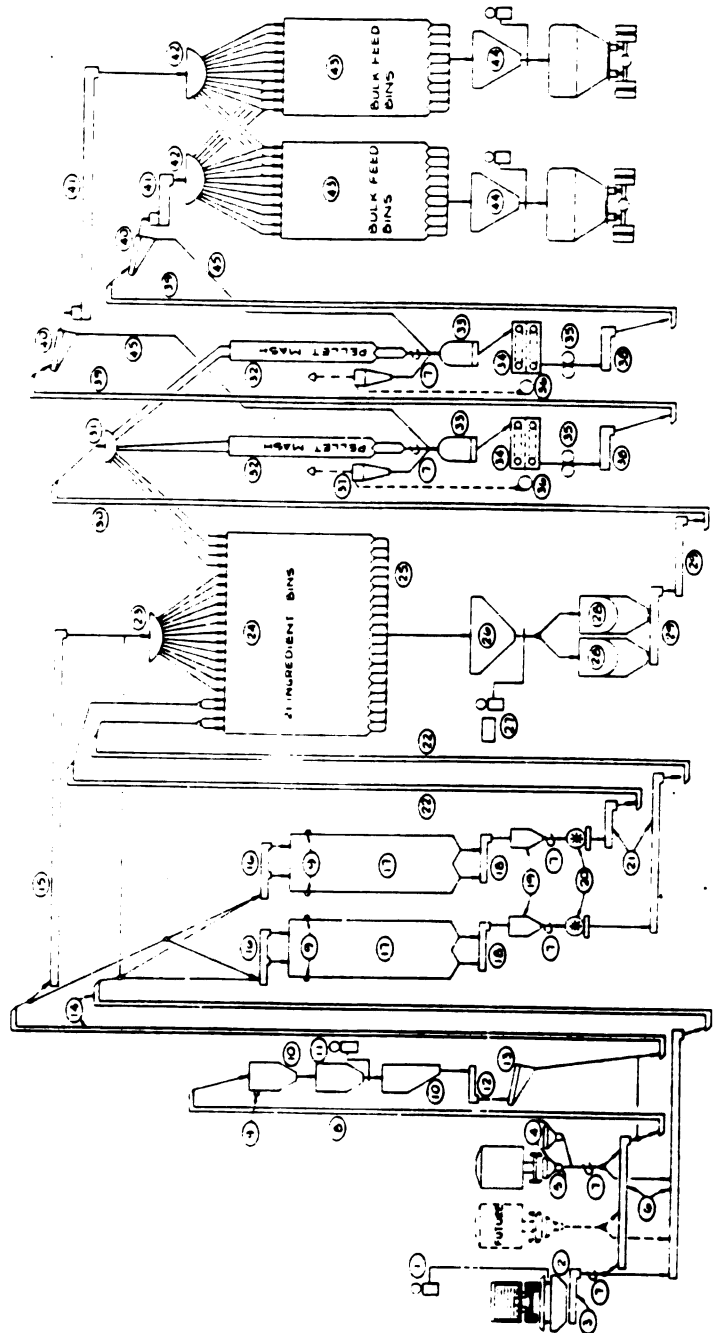


Fig. 3.1 - Feed mill process flow diagram (Balding, 1985).

**Table 3.1 - Connected Motor Horsepower for Various Processes
in a Feed Mill with a Capacity of 10-20 tons/h.**

<u>Centers</u>	<u>Connected Motor Horsepower</u>	
Receiving		60
Processing		
Grinding	160	
Cracking	25	
Steam Rolling	<u>190</u>	
Total Processing		375
Mixing		
Batch	120	
Continuous	<u>50</u>	
Total Mixing		170
Pelleting		300
Packaging		30
Bulk Loading		<u>30</u>
<u>Total Plant</u>		<u>965</u>
From McElhiney (1985)		

3.2 - The Pelleting Process

A typical flow diagram of the pelleting process is shown in Figure 3.2. Feed mash from an overhead bin flows into the feed conditioner where steam and binders are added. The conditioned mash flows into the pelleting mill in which the pellets are formed. The hot pellets pass to the cooler where they are cooled by ambient air. Fines carried by the cooling air are separated in a cyclone and returned to the feed mash to be reprocessed. The cool pellets are passed through the crumbler, if crumbled pellets are required. After the crumbler the pellets pass over a screen in a roto-shaker to remove the fines and overs. The pellets

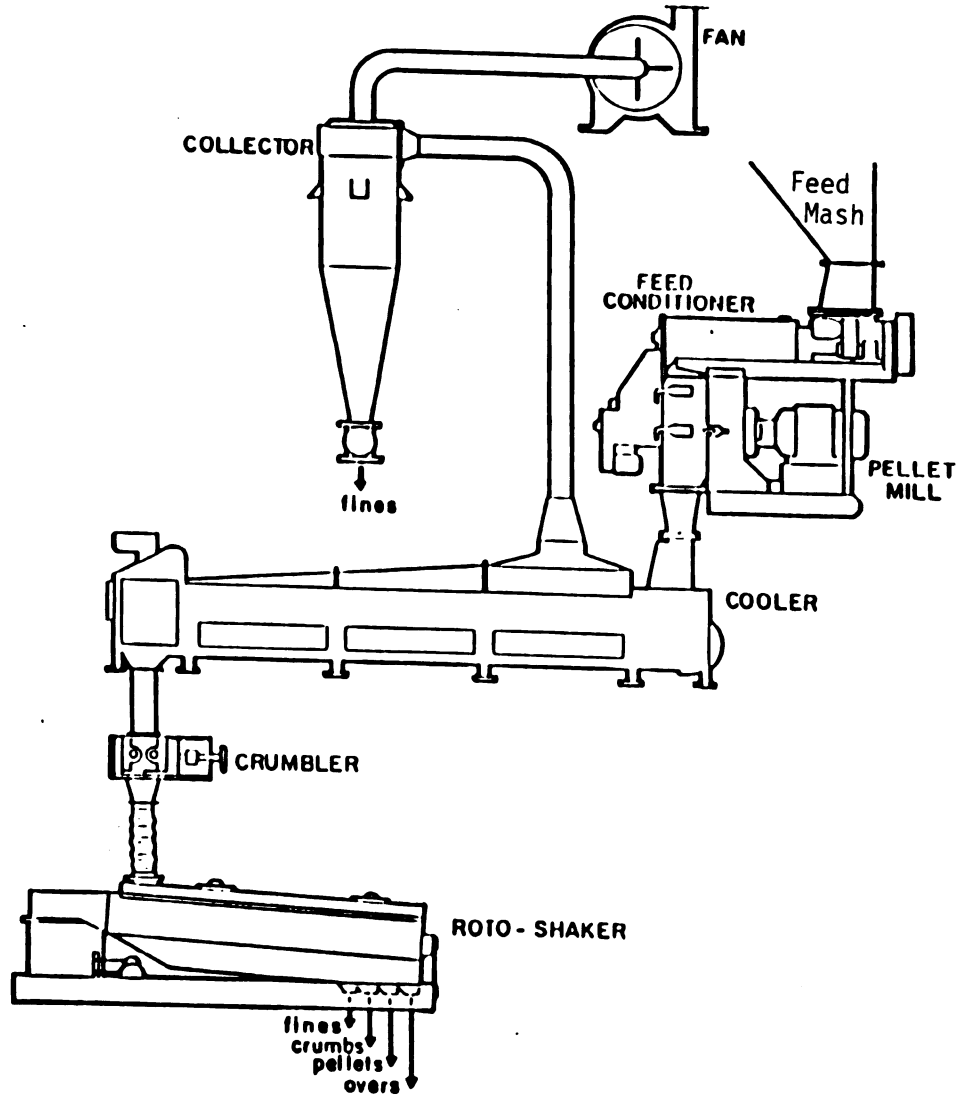


Fig. 3.2 - Pelleting process flow diagram (Falk, 1985).

flow into bins for conditioning, while the fines and overs are returned to the pellet mill to be reprocessed (Falk, 1985).

Table 3.2 lists the connected horsepower for the various electric motors used in a 10-20 ton/h pelleting system. The pellet mill uses 66% of the energy, while the cooling/drying system, including the cooler/dryer, the cooler fan, and the airlock, accounts for 17% of the energy consumption of the pelleting process. Therefore, only an improvement in the pellet mill can significantly reduce the final cost of the pelleted feed.

Table 3.2 - Pelleting System Connected Motor Horsepower for a Plant with a Capacity of 10-20 tons/h.

Driven Unit	Motor HP
Feed Conveyor	1.00
Mash Conditioner	7.50
Pellet Mill	200.00
Centri-Feeder	3.00
Cooler (Horizontal Belt)	1.00
Cooler Fan	50.00
Airlock	0.75
Crumble Rolls	20.00
Bucket Elevator	5.00
Shaker	3.00
Distributor	0.25
Pellet Coater with Pump	6.00
Conveyor	2.00
Distributor	0.25
Total Connected Motor HP	300.00
From McKilhiney (1985)	

Figure 3.3 shows the major components of a pellet mill: the variable feeder, the conditioning chamber, the die and roller assembly, the speed reducer, and the motor.

Pellet mills are available in a wide range of capacities, varying from 20 HP (14.9 kW) to 700 HP (522 kW) (Falk, 1985). The inside diameter of the pellet-die varies from 30.5 cm (12 in.) to 81.3 cm (32 in.). The working area of the pellet die ranges from 582 cm² (90 in.²) to 5,190 cm² (804 in.²). The pellet-mill capacity varies with the physical characteristics of the material being pelleted. It also depends on the number of time different formulas are pelleted, and on the number of die-changes per day. The average pellet-mill capacity is 68 Kg/HP-h (150 lb/HP-h) (Pfof, 1970).

Some products pellet readily while others require the addition of binders or lubricants to produce a stable pellet. Moisture content, density, and particle size contribute to the condition of the finished pellet. Other factors affecting the pelletability are: pellet-mill die-design, die-speed, and the mash flowrate.

The actual pelleting process consists of conditioning, compacting, extruding, cooling/drying, and conditioning. The pelleting process transforms finely divided materials into larger particles with a greater bulk density and improved flow characteristics.

The feeder is generally of the screw type, and is equipped with a speed-control device. In normal operations the screw-speed is over 100 rpm (Falk, 1985). The purpose of

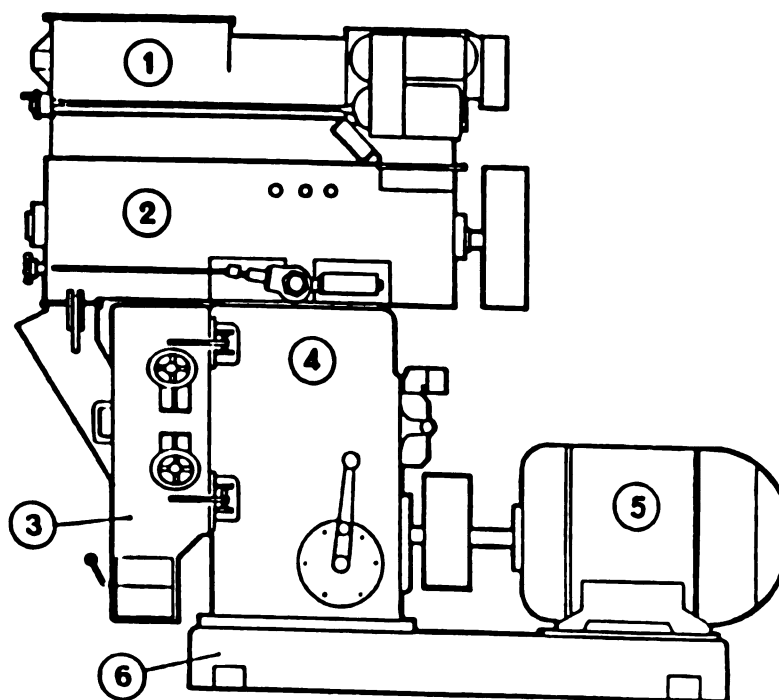


Fig. 3.3 - Components of a pellet mill (Robinson, 1971).

- 1 - Variable feeder
- 2 - Conditioning chamber
- 3 - Die and roller assembly
- 4 - Speed reduction device
- 5 - Motor
- 6 - Base

the feeder is to provide a uniform flow of feed to the mixing and pelleting operations.

Conditioning is an important step to improve the feed value, pellet durability, and power requirements of the pellet mill. The conditioning occurs in a mixer before the pellet mill, and is accomplished by the addition of steam, fat, or molasses to the mash. The flow-through mixer with either fixed or adjustable paddles, is equipped with steam manifolds and liquid injection ports. The mixer-shaft speed varies from 90 to 500 rpm depending on the material being pelleted. Steam used in conditioning process should be of a specific quality and have a constant pressure. Usually, high pressure steam ranging from 60 to 150 psig is introduced to the mixer through a steam harness designed to remove moisture and to ensure the required pressure. The addition of a conditioner ensures the pelleting of the mash, increases die-life, and reduces the power requirements (Robinson, 1971).

Figure 3.4 describes the boiler requirements of a pellet mill based on the percentage of moisture added to the pellet mash by the steam. This amount is usually less than 6% and varies with the type of feed pelleted (McElhiney, 1985).

The conditioning process of the meal results in an increase in the moisture content of the meal. About 1% moisture is added in the steam conditioning process for every 11 C (20 F) increase in temperature. In the case of dairy pellets, the addition of 8% of molasses adds 2% of

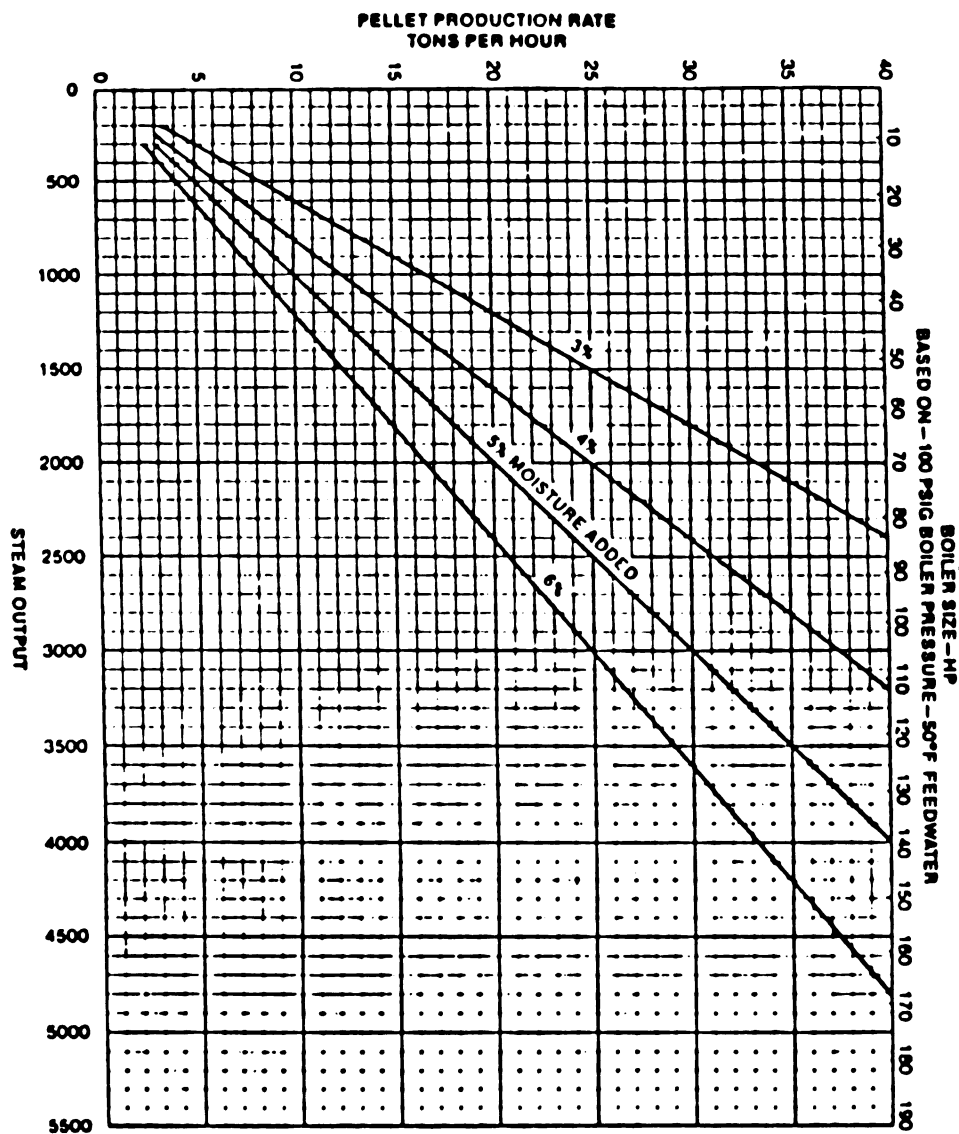


Fig. 3.4 - Boiler requirements based on pellet production and moisture addition (McElhiney, 1985).

moisture. In general, the moisture content of the pellets leaving a pellet mill varies from 15% to 18.5% (WB) (Atkinson, 1981b).

Table 3.3 shows the effects of fines and steam addition on the pellet-mill capacity (McBain, 1968). The results are the average of 100 tests on two typical high-corn content formulas and one natural 32% high-protein formula. The data shows that low pressure steam results in the highest capacity and quality for the high-corn formulations, whereas high-pressure steam is best for the high-protein formulation. At the higher pressure, less moisture is added by the steam.

Compaction of the feed mash is accomplished in the pellet mill by the action of rollers upon a perforated die face. The first pellet mill using steel dies and rollers was built on the principle of a flat steel die with four rollers running on the upper surfaces. The ring-type die and roller pellet mill was developed in the mid 1930's; it has become the most popular pellet mill in the pelleting industry (Robinson, 1971). Figure 3.5 shows a drawing of a ring-type die and roller pellet mill. The die-speed of a pellet mill normally ranges from 100 rpm to 400 rpm. The rotation of the rollers and die develops the force necessary to extrude the material through the die holes. The extruded product is cut off by knives adjustable in length to the desired pellet length.

Table 3.3 - Effects of Fines and Steam Addition on the Capacity of a 100 HP Pellet Mill.

Steam Pressure (PSIG)	Meal Temp. (F)	Condition. Meal Moist. (% WB)	Moisture Added (%)	Fines Over #16 Screen (%)	Pellet Mill Cap. (Tons/h)
Test #1					
Formula: Pig Grower (70% Corn)					
Dry Meal Bound Moisture: 10.8 %WB Die 3/16" x 2"					
50	190	12.8	2.0	9.7	8.5
20	190	14.0	3.2	4.3	7.0
14	202	16.3	5.5	2.3	8.5
Test #2					
Formula: Chick Grower (65% Corn)					
Dry Meal Bound Moisture: 11.9 %WB Die 5/32" x 1 3/4"					
75	180	13.4	1.5	7.5	7.0
40	190	14.1	2.2	6.2	7.5
16	195	16.6	4.7	2.5	10.0
Test #3					
Formula: 32% Steer Fattner					
Dry Meal Bound Moisture: 12.0 %WB Die 1/4" x 1 1/2"					
75	155	13.1	1.1	1.3	5.5
55	160	14.0	2.0	1.2	6.5
40	140	14.0	2.0	1.8	5.0
16	140	15.3	3.3	2.3	4.0
From McBain (1968)					

The commercially available die-sizes for cylindrical pellets range in diameter from 0.24 cm (3/32 in.) to 3.5 cm (1 3/8 in.). The pellet lengths are 1.5 to 3.0 times the diameter. For some of the large pellets sizes, square and oval shapes are available (Robinson, 1971).

Die-thickness is determined by the quality and production rate desired for the product being pelleted. A thick die normally produces a better quality product, but also reduces the production rate compared to that of the thinner dies. Products which are difficult to pellet, such

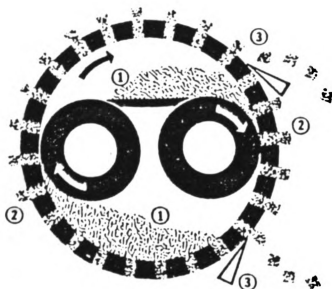


Fig. 3.5 - Schematic of operation of ring-type die and roller pellet mill (Robinson, 1971).

- 1 - Feed material
- 2 - Compacted and extruded feed
- 3 - Knives

as fiber and urea, are normally produced in thin dies, while grain products are most frequently pelleted in thick dies. The usual die-thickness varies between 3.2 cm (1 1/4 in.) and 12.7 cm (5 in.) (Falk, 1985).

The pellets leave the die at an elevated temperature between 65 C (150 F) and 93 C (200 F) because of the combined effects of the steam injected into the meal during the conditioning process and of the temperature rise resulting from the friction in the die (Atkinson, 1981a).

3.3 - Cooling of Pellets

After a feed has been pelleted, it is necessary to remove the excess heat and moisture to ensure safe long-term storage. The cooling and drying process is accomplished by moving ambient air through a bed of the warm, moist pellets.

The process objectives of a pellet cooler are (Trickett, 1982): (1) to reduce the temperature to just above the ambient air temperature; (2) to reduce the moisture content of the pellets to 12-14% DB; (3) to cool at a controlled rate to prevent overdrying of the pellet surfaces, and ensure pellet durability; (4) to operate effectively under a wide range of climatic conditions; and (5) to operate efficiently with the minimum usage of power.

Factors affecting cooler performance include (Whiteley, 1983): (1) cooler design (vertical, horizontal, crossflow, or counterflow); (2) air flow rate, air inlet

temperature, air inlet relative humidity; and (3) pellet flow rate, pellet size, pellet inlet temperature, and pellet initial moisture content.

Regardless of the inlet relative humidity of the cooling air, the relative humidity is decreased due to the heating of the air by the warm pellets. However, the absolute humidity of the air increases. Thus, the cooler removes moisture along with excess heat from the pellets.

Pellets are usually dried to 12% to 14% (DB) moisture content and to within 2 to 8 C (5 to 15 F) above the ambient temperature (Atkinson, 1981b; Falk, 1985).

The approximate cooling air requirement for various pellet diameters is listed in Table 3.4; the required retention time in the cooler of pellets of different diameter is shown in Table 3.5. Large diameter pellets require higher air flows and larger cooling times than smaller pellets because a larger path has to be traversed by the heat and moisture, in migrating from the inside to the outside, in large than in small diameter pellets (Falk, 1985).

Table 3.4 - Cooling Air Requirements for Various Pellet Diameters.

Pellet Diameter (in.)	CFM/Ton/Hours
10/64 to 12/64	800
1/4	900
3/8	1000
1/2 to 3/4	1100
7/8 to 1	1200

From Falk (1985)

Table 3.5 - Minimum Retention Time in a Cooler for Various Pellet Diameters.

Pellet Diameter (in.)	Retention Time (min)
10/64 to 12/64	5 to 6
1/4	6 to 8
3/8	7 to 8
1/2	8 to 10
3/4	12
7/8	15

From Falk (1985)

Pfost and Young (1973) investigated the effect of colloidal binders on the pellet durability and on the pellet energy requirement. This last quantity is also called the pelleting efficiency, and measured in lb/Kwh. Factors studied included the amount of steam or binding agent added, the granulation of the pelleted grain, and the cooling time. Table 3.6 shows the effect of cooling time on pellet durability. The percentage of fines refers to the damage of the pellets occurring in the handling system. Long cooling times resulted in fewer fines than short cooling times. At the low steam level, which corresponds to 30 F temperature rise and 1.4% moisture added to the mash, 24% fines was produced at an efficiency of 125 lb of pellets/Kwh. At the high steam level, corresponding to 90 F temperature rise and an addition of 3.9% in moisture to the mash, 10% fines was produced at an efficiency of 250 lb of pellets/Kwh. The use of betonite as a binding agent increased the durability but did not affect the pelleting efficiency.

Table 3.8 - Effect of Cooling Time on Pellet Durability.

Cooling Time (min)	Moisture Content (% WB)		% Fines
	Before Cooling	After Cooling	
5	14.4	11.4	10.5
10	14.3	11.8	8.5
15	14.5	10.8	8.6

From Pfost and Young (1973)

Whiteley (1983) studied the effects of air flow, residence time, bed depth, product size, and air inlet humidity, on the cooling and drying of .95 cm (3/8 in.) diameter pellets initially at 65 C (150 F) and 15% (WB) moisture content; cooling took place in a vertical and a single deck horizontal cooler. Table 3.7 shows some of the results. A high air flow rate cools the pellets faster; a long cooling time results in a cooler product. Also, a deeper bed improves the drying, and a smaller diameter pellet improves the cooling and removes more moisture content; and, the relative humidity of the cooling air has little effect on the moisture loss.

Improper cooling and drying can result in: (1) poor pellet quality, (2) pellet breakdown, (3) spoilage, (4) heating and spontaneous combustion in large volume storage, (5) caking in bags or bins, and (6) monetary loss from excess moisture removal (Robinson, 1983).

Table 3.7 - Effect of Air Velocity, Bed Depth, Residence Time on Pellet Temperature During the Cooling of Pellets in a Stationary Bed.

Air Velocity (ft/min)	Bed Depth* (in.)	Temperature (C) Above Ambient After Cooling Period (min)			
		5	10	20	30
40	2	17.5	7.0	3.0	1.0
	4	23.5	12.5	5.0	2.0
	6	27.0	17.0	8.0	3.0
	8	28.0	20.0	10.0	4.5
	10	29.0	22.0	11.5	6.0
60	2	13.0	5.0	1.0	1.0
	4	18.5	8.0	3.0	1.0
	6	22.5	12.0	4.5	1.5
	8	25.5	16.0	6.5	2.0
	10	26.5	17.0	8.5	3.0
80	2	8.0	4.0	1.0	1.0
	4	14.0	6.0	2.0	1.5
	6	17.5	8.0	3.0	1.5
	8	21.0	11.5	4.0	2.0
	10	23.5	14.0	5.0	2.5
120	2	8.0	3.0	1.5	-
	4	12.0	5.0	2.0	-
	6	16.5	7.0	2.5	-
	8	20.0	9.5	3.5	-
	10	21.0	12.0	4.0	-

* Bed depth measured in direction of air flow
From Whiteley (1983)

Pelleting is a cause of shrink in feed manufacturing operations. A part of the shrink is the result of moisture loss between the mash-feed inlet and the pellet outlet. Table 3.8 shows the results of typical cooling tests conducted by Wolfe (1982), as cited by McElhiney (1985a). Wolfe (1982) considered the level of shrink occurring in the feed manufacturing process to be directly affected by the cooling air temperature. The water-holding capability of the cooling air doubles for every 11 C (20 F) rise in

temperature. Thus, pellets can be cooled in a pellet cooler even on high relative humidity days. Figure 3.6 illustrates the effect of the average moisture content on the pellet temperature during a 12-month period.

Table 3.8 - Pelleting Moisture Loss.

Sample Location	Moisture (%WB)	
	Dairy w/ 2.5% Molasses	Dairy w/ 1% Molasses & Urea
Feed Inlet	12.80	13.30
Cond. Chamber with Molasses & Steam*	16.37	16.61
Die Discharge	16.67	16.81
Cooler Discharge	12.62	12.70
Moisture Loss	0.18	0.60
Value of Loss Based on		
\$ 150/ton Feed	\$ 0.27/ton	\$ 0.90/ton
*Molasses added at conditioner		
From Wolfe, cited by McElhiney (1985a)		

Figure 3.7 shows the average moisture content of pellets over a 3-year period. The moisture content of the pellets is lower during the warmer months when the ambient temperature is high (McElhiney, 1985a).

Dust particles exiting a pellet cooler are normally large and therefore easy to collect. To avoid breakage of the dust particles into smaller sizes and reduce fan impellor wear, the air system fans is located on the negative pressure side of the collector (McElhiney, 1985).

Pellet cooling takes place in a crossflow, horizontal belt, or counterflow cooler. In the following sections each of these cooler-types will be discussed in detail.

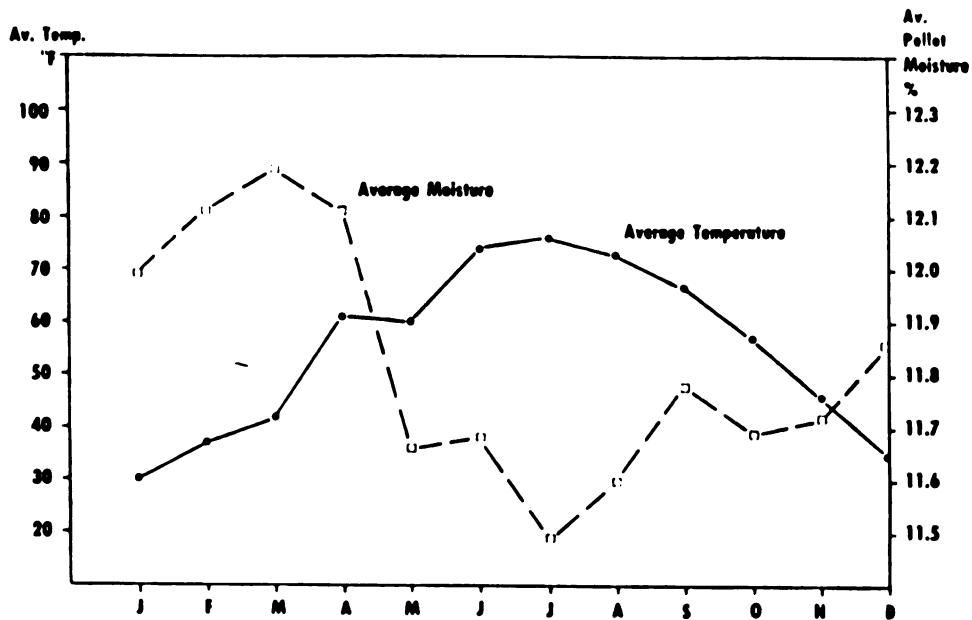


Fig. 3.6 - Graph showing average air temperature vs average moisture content of cooled pellets (McElhiney, 1985a).

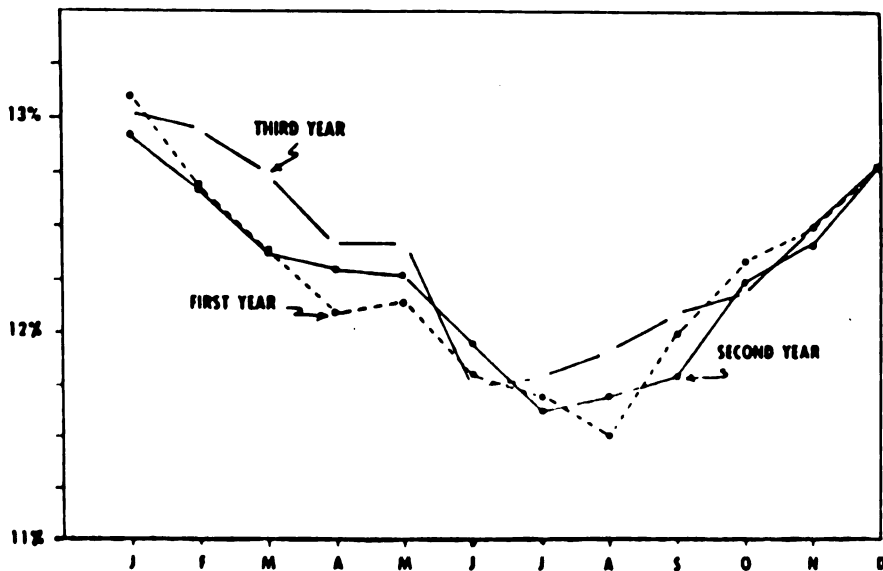


Fig. 3.7 - Graph showing average finished feed moisture content over a 3-year period (McElhiney, 1985a).

3.3.1. Vertical Crossflow Coolers

Figure 3.8 is a schematic of a vertical crossflow cooler. The supply hopper has a level-sensing device (1) which spreads the pellets over the width of the cooling column (2). The air is drawn through the screen-walled columns into a central plenum (3). The discharge drive gate motor (4) powers the discharge control mechanism (5) which is usually of the star-wheeled or vibratory type. The fan drive motor (7) centrifugal fan assembly draws the air through the pellets and discharges it into a cyclone for removal of the fines.

The cooler must have uniform air flow through the pellet columns and an uniform pellet flow. Cooling requires a high air volume and, therefore, has a high power requirement (Trickett, 1982).

Typical dimensions of a vertical cooler are: 140 cm (55 in.) to 152 cm (60 in.) wide, 198 cm (78 in.) to 518 cm (204 in.) high, with the thickness of the cooling columns varying from 23 cm (9 in.) to 25.4 cm (10 in.). The cooler capacity depends on the equipment dimensions, the air flow rate and the pellet size, and ranges from 3.5 to 22 tons per hour. A vertical cooler to cool and dry 8 to 13 tons of pellets per hour, requires a 40 HP fan and a pellet-flow control-gate powered by 1/4 HP variable speed motor (Robinson, 1970).

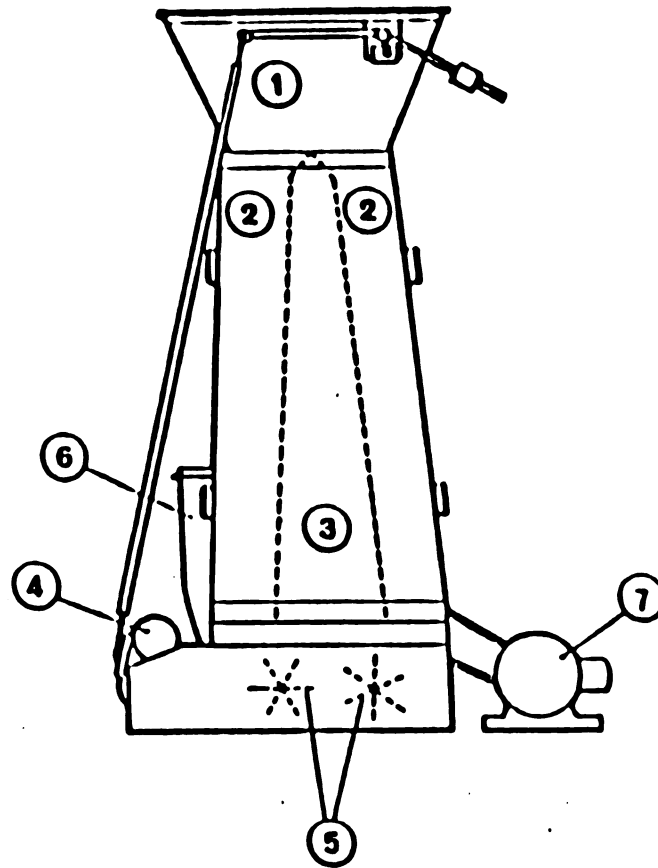


Fig. 3.8 - Vertical crossflow cooler (Robinson, 1971).

- 1 - Hopper and level sensing device
- 2 - Cooling column
- 3 - Plenum chamber
- 4 - Discharge gate drive motor
- 5 - Discharge augers
- 6 - Centrifugal fan
- 7 - Fan drive motor

Atkinson (1981) emphasized that the main problem with vertical coolers is that they need to be full to operate, and that the retention time is inversely proportional to the production rate. Thus, for a specific capacity of small versus large pellets, the retention time should be larger for the larger pellets. If, for instance, a cooler is designed to cool .95 cm (3/8 in.) diameter pellets in 20 minutes at a rate of 10 tons/h, .24 cm (3/32 in.) diameter pellets will be cooled at 5 tons/h remaining in the cooler for 40 minutes. Because of the small diameter and greater surface area, a period of 5 to 10 minutes would have been adequate for the smaller pellets; in 40 minutes excessive dehydration would occur. This problem may be solved by adding in the cooler a discharge mechanism which regulates the rate of discharge to correspond to the rate of pellets delivered to the cooler.

Trickett (1982) stated that the use of vertical coolers in hot humid climates is likely to lower product quality and shelf life.

3.3.2 - Horizontal Belt Coolers

In a horizontal cooler the pellets are carried on a moving perforated metal belt through the cooler while air is drawn through the layer(s) of pellets on the belt. Single, double, and triple belt coolers are used in the pellet mill industry.

The capacity of a belt cooler depends on the length,

width and depth of the bed(s). The width, usually four to seven feet, is limited by the requirement to spread the incoming pellet-flow evenly over the bed to ensure uniform cooling. In order to limit the length of a cooler, dual or triple passing is employed (Atkinson, 1981).

The pellets are delivered from the pellet mill to the cooler feeding device which spreads the incoming pellet flow evenly over the cooling belt and also controls the speed of the cooling belt. Therefore, the retention time will be different for each pellet type, thereby avoiding overdrying (Atkinson, 1981b; Robinson, 1983).

When pelleting high molasses, high fat, or urea pellets, a horizontal cooler should be used (McBain, 1968). In these cases, the weight of the pellets in the vertical cooler can cause caking of the pellets prior to the discharge and can lead to screen clogging.

3.3.2.1 - Single Deck Horizontal Coolers

In a single-deck horizontal cooler the cooling air passes only through one layer of pellets as in the vertical coolers.

Figure 3.9 is a schematic of a single-deck horizontal cooler. A bed of pellets 5 cm (2 in.) to 30.5 cm (12 in.) is evenly spread on a perforated belt (2) by the oscillating feeder (1). A level sensing device is incorporated in the design to start and stop the belt, thus maintaining a constant thickness of the cooling bed

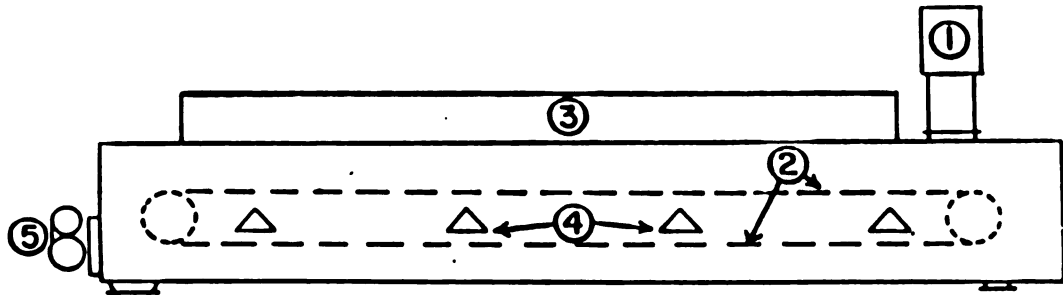


Fig 3.9 - Single deck horizontal cooler (Robinson, 1970).

- 1 - Oscillating feeder
- 2 - Product carrying belts
- 3 - Air chamber
- 4-- Air inlets
- 5 - Cooling belt drive

regardless of the production rate. Air flows through the pellets by means of a centrifugal fan, drawing air from the space below the cooling belt (4) to the plenum chamber (3). As in the vertical cooler, the cooling fan discharges the air into a cyclone for removal of the fines which are subsequently reprocessed.

The typical dimensions of a single-belt horizontal cooler are: .9m (3 ft) to 2.4 m (8 ft) wide, 3 m (10 ft) to 16.8 m (55 ft) long with a pellet bed adjustable to 5 cm (2 in.) to 30.5 cm (12 in.). The capacity varies from 2 to 60 tons/h, depending on pellet size and type of feed (Robinson, 1983).

The single-deck horizontal cooler requires about 1,000 CFM of air per ton/hour of pellets. Thus, a unit rated at 10 tons/h needs a fan and dust separation equipment capable of handling about 10,000 CFM. When less air is required to pass through the pellet bed due to a lower output, a lower temperature drop and/or a lower moisture decrease, a bypass valve is opened to prevent all the air from flowing through the cooler. This construction allows some air to be passed to the dust collector to avoid the possibility of condensation (Atkinson, 1981b).

3.3.2.2 - Dual-Deck Horizontal Coolers

The dual-deck horizontal cooler is usually constructed in a single enclosure with one air source. Figure 3.10 is an illustration of a dual-deck horizontal

cooler. The operation and components are the same as for the single-deck horizontal cooler, except that the dual-deck models have two carrying belts.

A dual-deck cooler is more efficient than a vertical and a single-deck horizontal cooler because the cooling air passes twice through the pellets. It cools pellets with approximately half the air volume of the single-deck cooler (500 CFM per ton/hour); however, the static pressure will be slightly higher (Trickett, 1982). Absorption of moisture of the exhaust air is higher in the dual-belt cooler than in the single-belt cooler because of the higher absolute humidity of the exhaust air.

3.3.2.3 - Multi-Deck Horizontal Coolers

A multi-deck horizontal cooler can be made in four, five or six deck versions (Trickett, 1982). It is the most efficient of the horizontal belt coolers in terms of cooling and drying. A four-deck horizontal cooler operates at one quarter of the air volume of a single-deck cooler, thus at 250 CFM per ton/hour of pellets. The average temperature of the exhaust air in a multi-deck cooler is much higher than in a single-deck cooler, about 56 C (132 F); this greatly increases the moisture carrying capacity of the exhaust air. The multi-pass cooler is the only existing pellet-cooler design that can successfully cope with the full range of climatic conditions encountered at many pellet mill locations (Trickett, 1982).

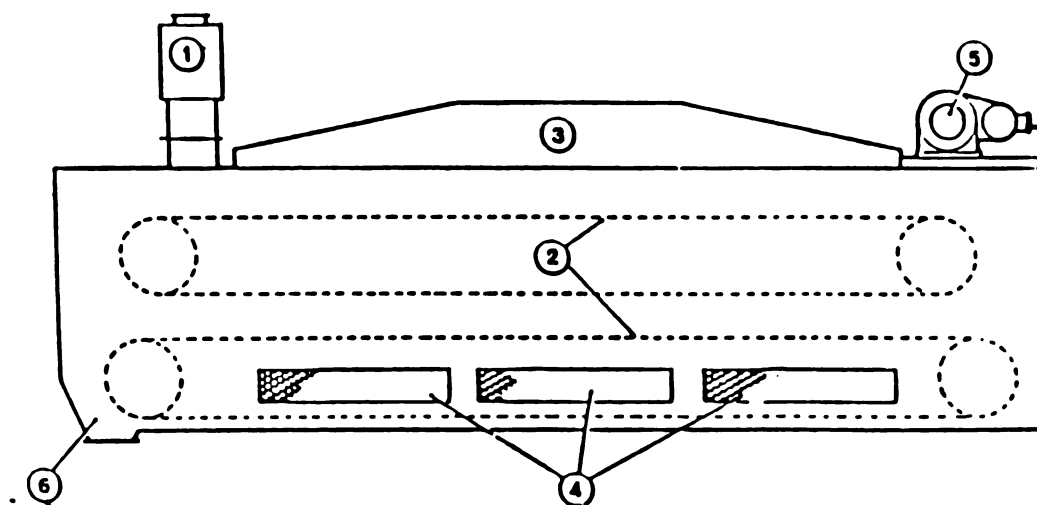


Fig. 3.10 - Dual-deck horizontal cooler (Robinson, 1971).

- 1 - Feeding device
- 2 - Perforated carrying belts
- 3 - Plenum chamber
- 4 - Air inlets
- 5 - Belt drive motor
- 6 - Discharge

3.3.3 - Cooler Comparison

Robinson (1983) compared vertical and horizontal coolers:

Vertical Coolers:

Advantages - lower first cost; relatively maintenance free; require less floor space.

Disadvantages - require more headspace; capacities limited unless multiple units are provided; tend to choke, bridge and channel with pellets of certain types of feed; no control on retention time as cooler must be full to properly function; the column thickness is nonadjustable; the output is a function of the pelleting rate.

Horizontal Coolers:

Advantages - basically unlimited in size; retention time is easily adjustable by varying bed-thickness; no bridging or channeling; require minimum headspace.

Disadvantages - high first cost; high maintenance cost.

Space limitation in the feed mill is a major criterion in selecting a cooler. Low ceiling-height and adequate floor-space favor a horizontal cooler (McBain, 1968).

Atkinson (1981b) stated that the use of horizontal coolers in the feed mill industry is increasing.

3.3.4 - Counterflow Coolers

A counterflow pellet cooler has been advertised by the Geelen Company (Geelen, the Netherlands) in the German journal *die Muhle and Mischfuttertechnik* (May, 1986). The counterflow cooler is manufactured in three models in capacities of 2.75 to 33 tons/h at bed depths from 25 cm (10 in.) to 147 cm (58 in.). The air volume is about 244 cubic meter per minute/ton or 800 CFM/ton.

The advantages of counterflow cooling according to the Geelen Company are: (1) the counterflow cooler saves up to 50% in energy compared to other cooler types, (2) requires less maintenance, (3) controls the cooling time more precisely, (4) requires less power, and (5) can be installed quickly into an existing pellet line.

No research has been reported on the topic of counterflow pellet cooling.

3.4 - Single Particle Drying Equations

In thin-layer drying experiments the drying behavior of a thin-layer of moist material exposed to constant external conditions - air at constant temperature, humidity, and flow rate - is observed over a period of time.

Sherwood (1936) observed that the drying process takes place in two or more distinct periods. First, in very

wet materials, there is a period during which evaporation occurs at a constant rate; this is followed by one or more periods in which evaporation continuously falls (Parry, 1985).

A comprehensive analysis of the constant-rate period, the falling-rate period(s), and the theories proposed for the transport of moisture in biological materials, is presented in Brooker et al. (1974), Fortes and Okos (1980), and Parry (1985).

The mathematical models proposed for describing the falling-rate drying period of biological materials, including pellets, may be divided into three categories:

- 1 - theoretical equations
- 2 - semi-theoretical equations
- 3 - empirical equations.

3.4.1 - Theoretical Equations

Simplifying assumptions made for Luikov's capillary-porous products drying model lead to the following equation in rectangular co-ordinates (Brooker et al., 1974 and Parry, 1985):

$$\frac{\delta M}{\delta t} = \frac{\delta}{\delta r} \left(D \frac{\delta M}{\delta r} \right) \quad (3.1)$$

where D is the diffusion coefficient, and M is the moisture content.

If a constant diffusion coefficient is assumed, equation (3.1) may be written as:

$$\frac{\delta M}{\delta t} = D \left(\frac{\delta^2 M}{\delta r^2} + \frac{c}{r} \frac{\delta M}{\delta r} \right) \quad (3.2)$$

where: c is zero for a slab, unity for a cylinder, and two for a sphere.

In order to solve equation (3.2), an appropriate geometric shape must be assumed for the representation of the individual product particles (e.g. rectangular, cylindrical, or spherical). Solutions to equation (3.2) for various solid shapes have been used as drying equations for solid biological materials to provide estimates of the average moisture ratio (MR) as a function of time (Crank, 1975). The MR is defined as:

$$MR = (M_t - M_e) / (M_o - M_e) \quad (3.3)$$

where: M_t = the average moisture content at time t
 M_o = the average (initial) moisture content at time = 0
 M_e = equilibrium moisture content (EMC).

The initial and boundary conditions usually assumed in solving equation (3.3) are of the form (Brooker et al., 1974):

$$M(r, 0) = M(in) \quad (3.4)$$

$$M(r_o, t) = M_e \quad (3.5)$$

In this study, pellets of cylindrical shape are used. Thus, with $c = 1$, equation (3.2) becomes:

$$\frac{\delta M}{\delta t} = D \left(\frac{\delta^2 M}{\delta r^2} + \frac{1}{r} \frac{\delta M}{\delta r} \right) \quad (3.6)$$

For conditions (3.4) and (3.5) and assuming negligible end effects, the average moisture ratio of the pellets is given by (Crank, 1975):

$$MR = \sum_{n=1}^{\infty} \frac{4}{\alpha_n^2} \exp\left(-\frac{\alpha_n^2}{R^2} D t\right) \quad (3.7)$$

where: α_n are the positive roots of the Bessel function of order zero, $J_0(\alpha_n) = 0$
 D = diffusion coefficient (m^2/h)
 R = radius (m)
 t = time (hour)

Equation (3.7) is used in this study to predict the thin-layer drying curve for pellets; it allows calculation of the moisture content after time t as a function of diffusivity (D) and pellet diameter.

A convective type boundary condition given by Brooker et al. (1974) can replace equation (3.5):

$$-D \frac{\delta M}{\delta r} = h_d (M_s - EMC) \quad \text{at } r = R \quad (3.8)$$

where: D = diffusion coefficient (m^2/h)
 h_d = convective mass transfer coefficient ($kg/h \ m^2$)
 M_s = moisture content at pellet surface (dec, DB)
 EMC = equilibrium moisture content (dec, DB).

The temperature gradients inside a pellet can be calculated by solving the heat conduction equation for constant thermal diffusivity without heat sources. The unsteady-state differential equation is (Rohsenow and Choi,

1961):

$$\frac{\delta \theta}{\delta t} = \alpha \left(\frac{\delta^2 \theta}{\delta^2 r} + \frac{1}{r} \frac{\delta \theta}{\delta r} \right) \quad (3.9)$$

where: θ = pellet temperature (C)
 α = thermal diffusivity = $k/d_p * C_p$
 k = thermal conductivity (W/h C)
 d_p = pellet density (kg/m^3)
 C_p = pellet specific heat (J/kg C).

Equation (3.9) is solved in this study assuming a boundary condition of the third kind which implies that the surfaces under consideration dissipate heat by convection according to Newton's law of cooling, i.e. heat transfer is proportional to temperature difference. Thus, the boundary condition has the form (Ozisik, 1980):

$$-k \frac{\delta \theta}{\delta r} = h (\theta_s - T) \quad \text{at } r = R \quad (3.10)$$

where: k = thermal conductivity (W/h C)
 h = convective heat transfer coefficient ($\text{W/m}^2 \text{-C}$)
 θ_s = pellet surface temperature (C)
 T = air temperature (C).

The initial condition is given by:

$$\theta(r, 0) = \theta(in) \quad (3.11)$$

3.4.2 - Semi-Theoretical Single Particle Equations

The solution to the diffusion equation (3.2) in spherical coordinates, with conditions (3.4) and (3.5), is (Crank, 1975):

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{D n^2 \pi^2 t}{R^2}\right) \quad (3.12)$$

Instead of an infinite number of terms, only the first term of Eqn. 3.12 is often used, resulting in the expression (Brooker et al., 1974):

$$MR = \frac{6}{\pi^2} \exp\left(-\frac{D \pi^2 t}{R^2}\right) = \frac{6}{\pi^2} \exp(-kt) \quad (3.13)$$

Alves (1985), Chhinnam (1984), Pabis and Henderson (1961), Sharaf-Eldeen (1979), Steffe and Singh (1980), and Young and Whitaker (1971) employed equation (3.13) in the study of drying grain and other agricultural products.

A second semi-theoretical expression often used is Newton's law of cooling; thus, for dehydration (Parry, 1985):

$$\frac{\delta M}{\delta t} = -k (M - M_e) \quad (3.14)$$

Integrating equation (3.14) and using equations (3.4) and (3.5), results in (Brooker et al., 1974):

$$MR = \exp(-kt) \quad (3.15)$$

Equations (3.13) and (3.15) are both called the drying equations; k , the drying constant, has units of hr^{-1} or sec^{-1} .

3.4.3 - Empirical Equations

Brook and Foster (1981), Brooker et al. (1974), and Parry (1985) compiled a number of empirical drying equations for biological products.

Thompson (1967) proposed for shelled corn in the temperature range of 140 to 300 F the following equation:

$$t = A \ln(MR) + B \ln(MR)^2 \quad (3.16)$$

where: $A = -1.86178 + 0.00448\theta$
 $B = 427.3640 * \exp(-0.03301\theta)$
 θ = product temperature (F).

Sabbah (1968) proposed for corn in the temperature range of 36 to 70 F:

$$MR = \exp(-k(t^{.664})) \quad (3.17)$$

where: $k = \exp(-x t^y)$
 x and y are θ and relative humidity dependent.

Nellist and O'Callaghan (1971) determined a two-term exponential equation for the drying of ryegrass seeds:

$$M = M_e + A \exp(-k_1 t) + B \exp(-k_2 t) \quad (3.18)$$

where A , B , K_1 , and K_2 are product constants.

Morey and Li (1984) investigated the effects of the thin-layer equation on deep bed drying prediction. The deep bed drying model developed by Bakker-Arkema et al. (1974) was used to evaluate the thin-layer equations proposed by Li and Morey (1984), Misra and Brooker (1980), Thompson (1967), and Sharaf-Eldeen et al. (1979). They concluded that the drying rate predicted with all these equations is slower

than the measured results, that the Li and Morey (1984) equation predict faster drying than the other equations, and that the thin-layer equation significantly affects the results derived from deep bed models.

Bruce (1985) obtained a set of thin-layer drying curves for barley at drying air temperatures from 50 to 150 C. Two empirical equations and a diffusion type equation with a time-varying boundary condition were fitted to the data. He concluded that: (1) the moisture loss data are described well by the diffusion model if the grain temperature rather than the air temperature is used to calculate the diffusivity; (2) the two empirical models do not describe the drying curves as well as the diffusion model; and (3) the diffusion model allows intra-kernel moisture movement calculation unlike the empirical models.

Thin-layer models are required for calculation of the drying rate of the individual particles in the deep-bed cooling/drying models (the subject of section 3.7).

3.5 - Pellet Properties

3.5.1 - Equilibrium Moisture Content (EMC)

The equilibrium moisture content (EMC) determines the moisture content to which a biological material is dried or wetted in a certain environment. Knowledge of the EMC is essential for simulating the cooling/drying of a bed of feed

pellets.

Berry and Dickerson (1973), Boquet et al. (1978), Hall and Rodrigues-Arias (1958), Headley (1969), and Nellist (1976) have determined the EMC for feedstuffs.

Empirical and semi-empirical equilibrium moisture equations have been proposed by Becker and Sallans (1956), Chung and Pfost (1967), Henderson (1952), Pfost et al. (1976), Nellist (1976), Smith (1947), and Thompson (1967). Parry (1985) reviewed the EMC models.

Boquet et al. (1978) and Chirife and Iglesias (1978) compiled the origin, range of applicability, and use of 23 equations reported in the literature for fitting the water sorption isotherms of foods.

Brook and Foster (1981) presented a tabulation of grain property values, EMC data, and EMC models available in the literature. Variations in the EMC reported for one grain at the same temperature and humidity are common (Brooker et al., 1974). The variations may be caused by the difference in the EMC determination methods or the chemical composition of the grain samples.

Errors in moisture content measurement or difficulties encountered in maintaining and measuring temperature and humidity while the sample equilibrates may cause experimental errors in the EMC determination. EMC values for desorption are different from those for absorption due to chemical or physical changes which take place upon drying to a low moisture content (Bakker-Arkema et al., 1978).

Desorption values are generally higher than adsorption. The difference between adsorption and desorption isotherms is called hysteresis. Several theories have been proposed to explain hysteresis. Chung and Pfoest (1967) suggested that hysteresis is due mainly to molecular shrinkage in the absorbent. Ngoddy and Bakker-Arkema (1970) and Labuza (1968) used the "ink-bottle" theory to explain the hysteresis effect.

Headley (1969) determined the EMC, using the static EMC method, of several pelleted feeds and feedstuffs, including cattle ration, high-urea cattle supplement, and high-urea cattle supplement coated with animal fat. All pellets were 3/16 in. in diameter. The temperature varied from 10 to 32 C (50 to 90 F) and the relative humidity ranged from 20 to 90%. Table 3.9 shows the results for the three pelleted rations.

Table 3.9 - EMC (%DB) of Pelleted Rations Measured at Various Temperatures and Relative Humidities.

	Temperature (F)										
	50				70				90		
	Relative Humidity (%)										
	40	58	75	82	35	55	76	80	32	51	76
Feeds*											
1	11.2	17.8	20.9	21.8	10.0	15.9	17.9	21.5	8.1	15.7	17.0
2	12.0	19.5	21.2	22.2	10.4	15.7	18.3	21.4	9.9	15.9	17.2
3	10.1	13.9	14.8	16.4	8.7	13.6	14.9	17.6	8.8	14.3	14.2

* 1 = Cattle Ration

2 = High Urea Cattle Supplement

3 = High Urea Cattle Supplement (surface coated)

From Headley (1969)

Headley (1969) compared the results of the pelleted rations with EMC data for corn and milo available in the literature. Except for the data for high-urea cattle supplement (surface coated), the results indicate that the EMC of pelleted rations is higher than of corn and milo.

Berry and Dickerson (1973) investigated the effects of particle size on EMC of laying mash and laying mash pellets. They concluded that at relative humidities up to 70% the pellets equilibrate at about .5% higher in moisture content than the mash.

According to Headley (1969), the reason why only limited EMC data for pellets is available, is due to the variation in the quantities of the different materials used in formulating livestock feeds.

Though empirical or semi-empirical models of EMC for various agricultural and food products have been developed, similar models for pelleted feeds are not known.

In this study three models - the Nellist (1976), the Modified Henderson (1952), and the Chung and Pfoest (1967) equations - are used to analyze the experimental pellet EMC data. The models were chosen because they have been widely used, are simple, have a limited number of parameters, and are temperature dependent.

3.5.1.1 - Nellist Equation

Smith (1947) used the Langmuir and the BET equations to model the EMC data for high polymers:

$$M_e = M_b - a \ln(1-RH) \quad (3.19)$$

where: M_b = maximum bound moisture content (decimal, DB)
 RH = relative humidity (decimal)
 M_e = equilibrium moisture content (decimal, DB)
 a = product constant.

Nellist (1976), investigating the EMC of ryegrass, proposed a modified version of the Smith EMC equation (3.19):

$$M_e = a - b \ln(1-RH) - c \ln(\theta) \quad (3.20)$$

where: a, b, c are product constants
 θ = product temperature (C).

3.5.1.2 - Modified Henderson Equation

Henderson (1952) proposed a semi-empirical model to predict the EMC of biological products. Using Gibb's adsorption equation the following equation was derived:

$$1 - RH = \exp(-a \theta_{abs} (M_e)^b) \quad (3.21)$$

where: M_e = equilibrium moisture content (% DB)
 θ = absolute product temperature (K)
 a and b are product constants.

Henderson's equation in its original form was found to be inadequate for cereal grains (Brooker et al., 1974). The modified form of the Henderson's equation was proposed

by Thompson (1967):

$$1 - RH = \exp(a*(\theta+b)*(M_e)^c) \quad (3.22)$$

where: θ = product temperature (C)
 a, b, c are product constants.

3.5.1.3 - Chung and Pfoest Equation

Chung and Pfoest (1967) developed an EMC equation based on the potential theory:

$$M_e = a - b * \ln(-(\theta+c) * \ln(RH)) \quad (3.23)$$

where: a, b, c are product constants
 θ = product temperature (C)
 M_e = equilibrium moisture content (decimal, DB).

3.5.2 - Diffusion Coefficient

The diffusion coefficient is a measure of the moisture flow in a biological product. It is a function of the product temperature and moisture content (Crank, 1975).

The units of the diffusion coefficient are usually given in terms of length² per time (l²/t).

The relationship between the diffusion coefficient and the product temperature is usually of the Arrhenius type (Brooker et al., 1974):

$$D = a * \exp(-b/\theta_{abs}) \quad (3.24)$$

where: D = diffusion coefficient (length²/time)
 θ_{abs} = product temperature (K)
 a and b are product constants.

Thus, as the product temperature increases, the diffusion coefficient increases.

Diffusivity is measured by collecting drying data of a particular biological product with respect to time.

It is frequently assumed that the diffusion coefficient of grain products is not affected by moisture content (Brooker et al., 1974). For feed pellets the same assumption is made in this study.

3.5.3 - Heat and Mass Transfer Coefficients

The values of h and h_d , the convective heat and mass transfer coefficients, are functions of the particle Reynold's number. Baker (1985) conducted an extensive literature review of the available theoretical and empirical relationships for the heat and mass transfer coefficients. The following equations were considered by Bakker-Arkema et al. (1967) to be the most satisfactory and are used for pellets in this study:

$$h = .992 Ga C_a Re^{-.34} \quad (3.25)$$

$$h_d = 15.5 Ga Re^{-1} Sc^{-2/3} (1 - \epsilon)^{1.2} \quad (3.26)$$

where:

- h = convective heat transfer coefficient (BTU/h-ft²-F)
- h_d = convective mass transfer coefficient (lb H₂O/ft²-h)
- G_a = air flow rate (lb/h-ft²)
- C_a = specific heat of the air (BTU/lb-F)
- ϵ = porosity of the deep bed
- Re = Reynolds number = $G_a D_i / \mu$
- Sc = Schmidts number = $\mu / D d_p$
- D_i = particle diameter (ft)
- μ = absolute viscosity (lb/ft-h).

3.5-4 - Thermal Conductivity and Specific Heat

Fortes and Okos (1982) investigating the drying of extruded corn at 30-70 C (76-158 F) and 8 to 36% DB, developed the following equations for the thermal conductivity and specific heat of this product:

For the thermal conductivity:

$$k = .1133 - 2.936 M^2 + 25.44 M^3 - 38.71 M^4 \quad (3.27)$$

and for the specific heat:

$$C_p = 4180 (.343 + M) / (1 + M) \quad (3.28)$$

where: K = thermal conductivity (W/m-K)
 C_p = specific heat (J/kg-K)
 M = moisture content (decimal, DB).

It is assumed that the k and C_p values for feed pellets are the same as for extruded corn.

3.5.5 - Latent Heat of Vaporization

Spencer (1971), simulating drying of wheat in a deep-bed, developed the following equation for the latent heat of vaporization as a function of the grain temperature and moisture content:

$$h_{fg} = (1065 - .55(\theta - 520)) (1 + 23 \exp(-4 \theta M)) \quad (3.29)$$

where: h_{fg} = latent heat of vaporization (BTU/lb)
 θ = product temperature (R)
 M = moisture content (decimal, DB).

It is assumed in this study that the h_{fg} for feed pellets is the same as for wheat.

3.5.6 - Air and Water Vapor Properties

The values of the density of air, and the specific heat of air, vapor, and water were obtained from thermodynamic tables (Threlkeld, 1962).

3.6 - Pellet Quality

3.6.1 - Nutritional Quality of Pellets

The nutritional value of pellets is affected by different factors including the equipment utilized, the conditions employed during the pelleting process, the nutritional value of the ration, and the animal itself.

Crampton (1956) observed that some animals have a tendency to select the coarse materials in a feed mixture from the fines. When small quantities of purified nutrients are added as supplement to a pelleted mixture, pellets should not disintegrate easily.

Calet (1965) reviewed the pelleting of poultry feed and its relative value versus mash and grain, and concluded

that pellets reduce wastage, improve feed conversion, improve feed digestibility, and increase the retention of nutrients.

Slinger (1972) and Pepper et al. (1960) studied the effects of pellet use in the diets of chickens and turkeys, and concluded that significantly less concentrate was consumed with pellets than with mash, although more weight was gained with the pellets.

Jensen et al. (1962) investigated the pelleting of wheat bran and noted an increase in feed intake of chickens; this led to an increase in weight gain and a decrease in the feed/gain ratio. They pointed out that the improvement was probably due to an increase in the bulk density of the feed, resulting in less time and energy expended for eating.

Kling et al. (1985) investigated the effect of pelleting the feed of chickens on egg production and size, and concluded that neither the egg-production nor egg-size was affected by the physical form of the feed.

Olsen and Slinger (1968) and Saunders et al. (1969) found that most of the feed intake improvement in rats from steam pelleting wheat bran and shorts is due to the increased availability of the contents of the aleurone layer.

Perry (1984) investigated the effect of pelleting a swine diet containing corn, soybeans, and barley. The pelleted diet produced a 14% faster and 15% more efficient gain than the same unpelleted diet.

Ensminger (1985) stated that in diets containing a

low level of crude fiber, there is no advantage in pelleting feed for beef cattle and swine. However, with more fibrous feeds, especially barley, there is a decided advantage in pelleting feed for swine.

Rinehart (1981) reviewed the effect of pelleting on feed value, and observed that the nutritional value of pelleting is due to the mechanical pressure and heat production of the process rather than to the form of the ration. He also noted that pelleting increases the feed intake of animals, and improves the feed conversion. Nutrient destruction and decreased nutrient availability were mentioned as potential disadvantages.

Slinger (1972) observed that during the formulation of least-cost rations the nutritional value of the pelleted feed and not the mash feed should be considered. In determining nutrient requirements, the pelleted feed should be used.

Cassard and Juergenson (1963) listed the advantages and disadvantages of the pelleting compared to the grinding of grains. The advantages are: larger feed intake (especially with high roughage rations), increased gain, increased feed efficiency, no sorting of the ration by the animals, easier mechanical feeding, reduced labor requirement, reduced waste, easier handling, reduced storage space, greater net energy availability, and reduced dust production. Disadvantages are: the cost of grinding and pelleting, the reduced rumination in cattle sometimes leading to digestive troubles, and the cost of handling

bulky ingredients to the mill for pelleting.

3.6.2 - Physical Quality of Pellets

The physical quality of pellets from the producers' point of view concerns the hardness, the lack of fines, and the ability to withstand physical deterioration during handling and feeding operations (Slinger, 1972).

The ingredient characteristics which affect the physical quality of the pellets include the fat-, fiber-, and protein-contents, and the texture of the mix (McBain, 1968). The fat content may refer to natural fat, which is already a feed ingredient, or to added fat; adding 1% fat to a feed mixture has a greater effect on pellet quality than the 1% fat already present in the mixture. Fiber is considered a natural binder; a high-fiber feed produces high quality pellets but results in a low production rate. Feeds with a high protein content have a relatively high bulk density because they plasticize as the mix passes through the die during pelleting.

Bulk density is a major factor in pellet production. For example, a 100 HP mill pelleting 100% dehydrated alfalfa at 272 Kg/m³ (17 lb/cft), can pellet 4 to 5 tons/h; the same mill pelleting 100% solvent extracted cottonseed meal at 580 Kg/m³ (35 lb/cft) to 640 Kg/m³ (40 lb/cft) can pellet 16 to 17 tons/h. Also, pelleting materials with high density require less power for the pellet mill than pelleting of low density materials (McBain, 1968).

The texture (or granulation) includes three general categories: coarse, medium, and fine grinds. ASAE Standard:R246.1 (1984b) defines coarse as the remaining material, after screening, on the 3/8, 4, and 8-mesh screens; that on 14 and 28-mesh screens as medium, and that on 48 and 100-mesh screens and in the pan as fine. Medium and fine grinds generally result in a higher pellet-mill capacity and an improved feed compared to that made from a coarse grind. The reasons are a greater surface area for absorption of moisture from the steam, and a higher starting bulk density provided by the medium and fine grinds.

Table 3.10 lists the common ingredients used in pelleted feeds (Falk, 1985). The chart can be used to rate the pelletability of single ingredients. Also, it is possible to determine the characteristics of a feed formula based on the percentage of the ingredients used. A composite rating provides an approximate capacity rating for a feed formula. The physical quality of a certain type of pellet will change when the content of the ingredients changes. The fat, fiber, and protein contents provide a key to the pellet quality. The column "abrasiveness" gives an indication of how an ingredient will affect die life.

Pellet durability tests are important to determine the pellet quality and are used to designate pellet resistance to breakage. The equipment utilized to obtain the pellet durability is described in ASAE Standard:S269.3 (1984b).

Table 3.10 - Pelletability Chart (Falk, 1985).

Product	Weight per cu. ft.	Percent Protein	Percent Fat	Percent Fiber	Pellet- ability	Abrasive- ness		Molasses Absorbability
						Degree	Reason	
Alfalfa Dehydrated	12-19	20	3.0	20	Med	High	LGC	40%
Barley	33	10	2	6	Med	Med	HGC	
Beet Pulp	16-20	8	.5	20	Low	Med	WBP	
Blood Meal	35-40	80	1	1	Med	Low		
Brewers Grain	15	24	6	15	Low	Med	WBP	9%
Buttermilk	31	32	5	0	Low	High	CHEM	
Citrus Pulp	20	6	2.5	15	Low	Med	WBP	
Coconut Meal		20	6	11	Low	High	CHEM	33%
Corn	40	8.4	3.8	2.5	Med	Low	HGC	15%
Corn Cob & Meal	35	7	3	8	V Low	V High	NAY	
Corn Gluten Feed	25	21	1.6	8	Med	Low	WBP	7%
Corn Gluten Meal	30	62	4	4	Med	Low	WBP	
Corn Oil Meal	35	18.5	1	11.5	High	Low	HGC	
Cottonseed Meal Solv.	35-40	41	1.5	13	High	Low	HGC	15%
Cottonseed Meal Exp.	35-40	36	4	16	Med	Med	HGC	
Distillers Grain	18	26	8	12.5	Low	Med	WBP	5%
Distillers Solubles		27	8	3	Med	Med	WBP	
Fish Meal	35	66	8	1.5	Med	Med	CHEM	
Hominy-Yellow	26	10	2.5	3.7	Low	Low	WBP	22%
Kafir Corn	40-45	11	2.5	2.5	High	High	LSC	
Kafir Head Chop		10	2	7	Low	High	LGC	
Linseed Meal Exp.	27	32	3.5	8	High	Low	HGC	9%
Linseed Meal Solv.	33	34	2.0	8	High	Med	CHEM	7%
Meat Scrap	41	55	9	2.5	High	Low		
Milo Maize	40-45	11	2.5	2.5	High	High	LGC	
Milo Head Chop		10	2	7	Low	High	LGC	
Molasses								
Oats-ground	30	13	3.5	12	Med	Med	HGC	20%
Oat Hulls	8	15.5	5	36.5	V Low	High	NAT	
Oat Screening	8-12	3.5	1	34	V Low	High	NAY	
Peanut Meal Solv.	40	50	5	7	High	Low	WBP	
Rice Bran	21	14	.6	15.5	Low	High	CHEM	
Rice Polishings	45-56	11	10	4	Med	High	CHEM	
Soyabeans Meal Exp.	40	42	3.5	6	High	Low	WBP	10%
Soyabeans Meal Solv.	40	45	5	High	Low	WBP	5%	
Wheat-Gray Shorts	15	16	3.5	6.5	Med	Low	WBP	
Wheat-Red Dog	28	1.6	3.5	3	Med	Low	WBP	
Wheat-Brown Shorts	15	15	3.5	8	Med	Low	WBP	
Wheat-Midds	20	15	3.5	8	High	Low	WBP	
Wheat-Flour	31	14	2	1	Med	Low	WBP	
Wheat-Bran	11-18	14	3.5	11	Low	Low	WBP	15%
Whey-Dried	36	12	.5	0	Low	High	CHEM	
Bone Meal	48							
Dicalcium	43							
Urea	40							

Abbreviations: CHEM - Chemical reaction plasticity

LGC - Low grown crops

HGC - High grown crops

NAT - Naturally abrasive

WBP - Washed by-product

In a pellet durability test a 500 g (1.1 lb) sample of whole pellets is placed in tumbling box (30x30x7.5 cm). After tumbling for 10 minutes at 50 rpm, the sample is removed, sieved, and the percentage of whole pellets is determined. The pellet durability is defined by:

$$\text{Durability} = \frac{\text{Mass of Pellets After Tumbling}}{\text{Mass of Pellets Before Tumbling}} (100) \quad (3.30)$$

The percentage of fines is determined by screening the pellets on a wire sieve with openings slightly smaller than the nominal pellet diameter. Table 3.11 shows the recommended sieves for pellets of various diameters.

Table 3.11 - Screens Sizes for Pellet Durability Tests.

Diameter of Pellets (mm) (in.)		Required Size	Screen (mm)	Size (in.)
2.4	0.094	No. 10	2.0	0.079
3.2	0.125	No. 7	2.8	0.111
4.8	0.188	No. 5	4.0	0.157
5.2	0.203	No. 4	4.8	0.187
6.4	0.250	No. 3.5	5.7	0.223
12.7	0.500	7/16	11.1	0.438

From ASAE Standard: S269.3 (1984b)

Normally, pellets are tested immediately after cooling. If tested at a later time, the time will be indicated by a subscript. For example, if the pellet durability tested 95 four hours after cooling, then the

durability is expressed as $(95)_4$.

If pellets are tested before cooling, there will be a significant weight-loss caused by water vaporization; the durability will be decreased by the loss of moisture. The loss of moisture must be evaluated by determining the moisture content before and after tumbling, and compensating for the final mass accordingly. When this procedure is followed, the durability is expressed as $(95)_{-1}$ (Falk, 1985).

The pellet durability index of pellets stored under equilibrium relative humidities ranging from 22% to 92% and temperatures from 10 C (50 F) to 33.2 C (90 F) was investigated by (Headley, 1969). The relative humidity range from 55% to 75% resulted in better pellet durabilities than those obtained at higher or lower relative humidites.

3.7 - Deep Bed Models and Simulation

Deep bed models are generally divided into three types: (1) logarithmic, (2) heat and mass balance (HMB), and (3) partial differential equation (PDE) models (Parry, 1985).

The first two models are of an empirical or semi-empirical nature, and require little computer time. However, the product temperature and moisture profiles are predicted inaccurately (Bakker-Arkema, 1984; Sharp, 1982). Therefore, both logarithmic and heat mass balance models are

limited in their range of applicability (Parry,1985). The HMB model is used in this thesis because it is suitable for PC-size computers.

3.7.1 - Algebraic or Heat and Mass Balances (HMB) Model

Thompson et al. (1968) first proposed a deep-bed drying model for grain based on heat and mass balances. The model first calculates an equilibrium drying temperature based on the sensible heat balance between air and grain; subsequently, the equilibrium moisture content and the drying rate of the grain are estimated using this temperature.

The equations proposed by Thompson et al. (1968) are presented in this section.

The drying air temperature is the equilibrium temperature of the drying air and the grain. It is calculated by performing a heat balance on each layer and has the form:

$$T_e = \frac{(1.005 + 1.884 H_o) T_o + C_p \theta_o}{1.005 + 1.884 H_o + C_p} \quad (3.31)$$

where:

T_e = equilibrium air temperature, K
 T_o = initial air temperature, K
 H_o = initial air humidity ratio, Kg/Kg
 C_p = specific heat of product, KJ/Kg K
 θ_o = initial product temperature, K.

The final moisture content is calculated by using a single-layer drying equation (Eqn. 3.7), and the equilibrium moisture content equation (Eqn. 3.22).

The final air and grain temperatures are assumed to be equal and are determined by:

$$T_f = \frac{(1.005 + 1.884 H_o) T_e - DH(2467.4 + h_{fg} + 273.16 - T_e) + C_p T_e}{1.005 + 1.884 H_f + C_p} \quad (3.32)$$

where:

T_f = final product temperature, K
 T_e = equation (3.31)
 h_{fg} = latent heat of vaporization, KJ/Kg
 H_f = final air humidity ratio, Kg/Kg

and

$$DH = H_f - H_o = \frac{(M_o - M_f) D_m}{100 G_a t} \quad (3.33)$$

where:

M_o = initial product moisture content, % DB
 M_f = final product moisture content, % DB
 D_m = product dry matter in each layer, Kg
 G_a = air mass flow rate, Kg/ min
 t = time step for simulation, min.

Noomhorn and Verma (1986) used the Thompson et al. (1968) model to evaluate the influence of two generalized single-layer equations on the drying rate of a fixed-bed of rice. They concluded that both equations underpredicted the moisture content; the rice temperatures were higher than the observed values, and the largest difference was observed at the top layers.

3.7.2 - Partial Differential Equation (PDE) Models

The development of stable computational techniques and the increasing power of modern computing have encouraged researchers to implement drying and cooling models of the PDE type. These models are formulated according to the standard laws of heat and mass transfer, and are of a more fundamental nature than the algebraic (HMB) models.

In the development of the deep-bed drying model for stationary bed the following assumptions are made: (1) particle to particle conduction is negligible, (2) there are no temperature or mass gradients in the y- and z-directions, (3) the heat capacities of moist air and of grain are constant during short periods of time, (4) the airflow is plug type, (5) $\delta T/\delta t$ and $\delta H/\delta t$ are negligible compared to $\delta T/\delta x$ and $\delta H/\delta x$, and (6) accurate thin-layer drying and moisture equilibrium equations are known (Bakker-Arkema et al., 1967; Brooker et al., 1974; Sharp, 1982).

The PDE models of the drying, cooling, and heating of a deep-bed of biological products such as feed pellets consist of four to six differential equations, depending on the assumptions made in the analysis. For a stationary bed of pellets in which the airflow is of the plugflow type the following simulation has been proposed (Brooker et al., 1974):

$$\frac{\delta H}{\delta x} = - \frac{d_p}{Ga} \frac{\delta M}{\delta t} \quad (3.34)$$

$$\frac{\delta T}{\delta x} = \frac{-h SA}{Ga(C_a + C_v H)} (T - \theta) \quad (3.35)$$

$$\frac{\delta \theta}{\delta t} = \frac{h SA (T - \theta)}{d_p(C_p + C_w M)} - \frac{h_{fg} + C_v(T - \theta)}{(C_p + C_w M)} - Ga \frac{\delta H}{\delta x} \quad (3.36)$$

$$\frac{\delta M}{\delta t} = \text{single pellet drying equation} \quad (3.37)$$

For a bed of depth L, the appropriate initial and boundary conditions are, respectively:

$$M(x,0) = M_1(x), \quad \theta(x,0) = \theta_1(x) \quad 0 < x < L \quad (3.38)$$

$$H(0,t) = H_1(t), \quad T(0,t) = T_1(t) \quad t > 0 \quad (3.39)$$

Equations (3.36) and (3.37) compute the average product temperature and moisture content values, respectively.

In the solution of the model (Eqns. 3.34 - 3.39) the deep-bed is divided into layers. Each layer is assumed to be of uniform moisture content and temperature; the inlet conditions for a layer are the outlet conditions of the previous layer. Numerical techniques are applied to solve

the set of differential equations for each layer. Carnahan et al. (1969) and Ozisik (1980) describe the numerical methods for solving such systems of differential equations.

Bakker-Arkema (1984) and Brooker et al. (1974) presented the PDE models for the basic grain cooler/dryer configurations of the fixed bed, crossflow, concurrent flow, and counterflow.

Parry (1985) and Sharp (1982) reviewed the deep bed models which have been employed in the simulation of heat and mass transfer in biological products.

Bakker-Arkema et al. (1984) used a counterflow model to analyze the cooling of grain; the simulation model accurately described the counterflow cooling process. The airflow rate and cooling air temperature significantly affected the exit grain temperature but not the exit grain moisture content; the relative humidity of the cooling air neither affected the exit grain temperature nor the exit grain moisture content.

3.7.3 - Psychrometrics

The topic of psychrometrics is important to the understanding drying and cooling of biological products. Professional organizations, such as ASAE (1984a) and ASHRAE (1977), have published psychrometric charts, tables, and equations.

Since charts and tables are not suitable for the applications of computer-aided design and simulation, a

standard computer model of the psychrometric chart is needed.

Brooker (1967) and Wilhelm (1976) have compiled thermodynamic and empirical equations which describe the psychrometric chart. The equations have been programmed as a computer subroutine for use in grain drying simulation programs (Brooker et al., 1974). Bakker-Arkema et al. (1974) published a package of psychrometric subprograms in SI units.

Chau (1980) proposed new empirical psychrometrics equations for the saturation temperature given the saturation vapor pressure and the wet-bulb temperature, or the dew-point temperature and dry-bulb temperature.

3.9 - Statistics

The statistical package Bio-Medical Data Processing (BMDP) program BMDPAR (Dixon, 1981) estimates the parameters of a nonlinear function by a least squares technique using a pseudo Gauss-Newton algorithm. The program is suitable for functions not linear in the parameters; it does not use the derivative of the function.

The information provided by BMDPAR includes the total number of data points, the number of data points in the analysis, the standard deviation, the mean, the minimum and maximum of each variable, and the residual sum squares for each iteration. The program calculates a linear function equal to the given function, using an improved set of

parameters. This process is repeated until convergence, or the specified number of iterations, is reached.

The following results are printed out: the best set of parameters encountered, the estimated mean square error, the estimated asymptotic correlation matrix, the estimated standard deviation for each parameter, and the estimated and observed value at each data point. If required, the program draws simple graphs of the predicted values and the residuals.

When the predicted values, obtained by a prediction equation using the estimates of the parameters, are compared with the observed values, and result in the smallest residual sum of squares, the estimate of the parameters is said to be the best set of parameters.

The criterion used to evaluate goodness of fit is the average of the relative percent difference between the experimental and predicted values. For instance, for the case of the EMC data points, the mean relative deviation modulus (P) is defined by the following equation (Lomauro et al., 1985):

$$P = \frac{100}{n} \sum_{i=1}^n \frac{|EMC_i - EMCP_i|}{EMC_i} \quad (3.40)$$

Where:

EMC_i = equilibrium moisture content at observation

$EMCP_i$ = predicted equilibrium moisture content at observation

n = number of observations.

The value of P is minimized when the error sum of squares is minimized in the selection of the equation parameters. The P value is an indication of the goodness of fit. A P value of less than or equal to 5 is considered to be a good fit (Lomauro et al., 1985).

3.10 - Summary

The review of literature has emphasized the cooling process of feed pellets. The following are the principal findings relevant to the current study:

- The pellets should leave the cooler within 5 C (10 F) of the ambient temperature and should be stable at that temperature.

- The pellets should be at a moisture level such that at average ambient temperature and humidity they remain at a constant weight.

- The pellet moisture content should be sufficiently low to avoid mold growth.

- The retention time in a pellet cooler is a function of pellet size, initial temperature and moisture content; the amount of heat to be removed is a function of formulation, steam addition and die friction; and, the ability of the air to cool and dry is a function of the flow rate, temperature and relative humidity.

- Space limitation is one of main points to be considered when selecting a pellet cooler; horizontal

coolers are high in initial cost but need limited vertical space; also, they are flexible since the retention time is easily adjustable.

- No simulation models are available in the literature for the cooling of feed-pellets.

- The equilibrium moisture content and the single pellet drying/cooling equations are required for the solution of the simulation models for pellet coolers.

4 - MODEL DEVELOPMENT

The following sections present the development of two pellet cooling simulation models.

4.1 - Model #1 - Heat and Mass Balance (HMB) Model

The development of this model is based on the approach followed by Thompson et al. (1968). The deep-bed of pellets is assumed to consist of a series of thin-layers positioned normal to the direction of the air flow. No heat transfer is assumed to occur through the cooler walls. The cooling air passes through a thin-layer of pellets in a specific cooling-time interval. The average pellet temperature is assumed to be equal to the temperature of the air surrounding the pellet. The thin-layer cooling/drying equation and the moisture equilibrium equation are known.

The relationships used in the development of this model are: (1) equation (3.31) for the equilibrium air temperature, (2) equation (3.7) for the drying rate, (3) equation (4.1) for the absolute humidity ratio, and (4) equation (3.32) for the pellet temperature. The flow diagram of the heat and mass balance stationary bed pellet cooling model is shown in Figure 4.1.

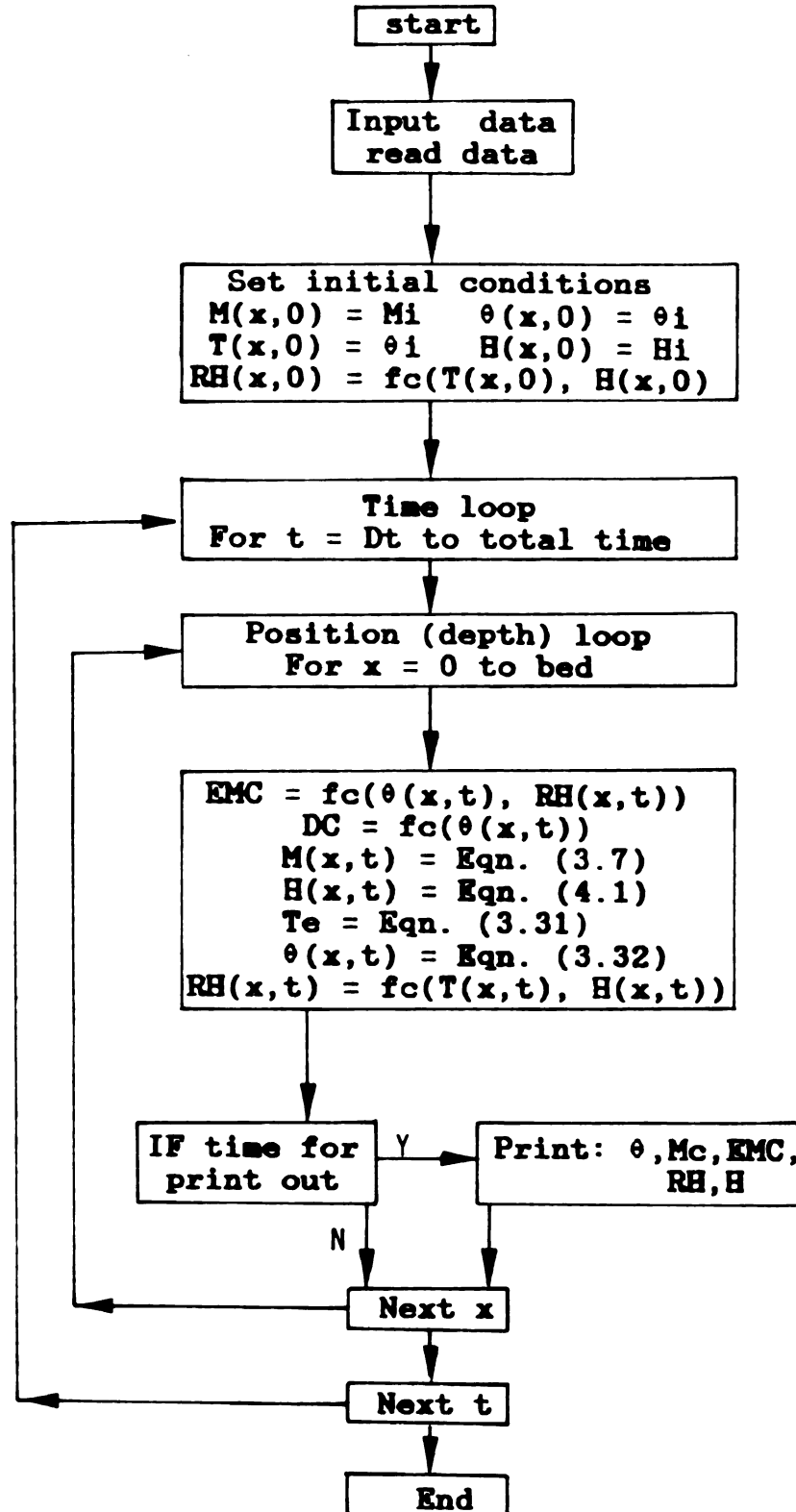


Fig. 4.1 - Flow diagram of the HMB stationary-bed pellet cooling model.

4.2 - Model #2 - Partial Differential Equations (PDE) Model

The equations used in PDE stationary-bed pellet cooling model to simulate the cooling of a fixed bed of pellets are: equations (3.34) through (3.37) with initial and boundary conditions (3.38) and (3.39). To determine the moisture content and temperature gradients inside the pellets, equations (3.6) and (3.9) with initial conditions (3.4) and (3.11) and boundary conditions (3.10) and (3.11), respectively, are employed. Since the set of equations can not be solved analytically due to non-linearity, numerical techniques are used to obtain the solution of the set of equations.

In order to compute the air temperature (T), absolute humidity (H), pellet temperature (θ), and average pellet moisture content (M) at each Dx location at time t+Dt within the cooler, the equations (3.34) to (3.37) are written in finite-difference form using forward-difference formulae.

Thus,

$$H_{x+1,t} - H_{x,t} = - \frac{dp \, Dx}{Ga \, Dt} (M_{x,t+1} - M_{x,t}) \quad (4.1)$$

$$T_{x+1,t} - T_{x,t} = \frac{- h \, SA \, Dx}{Ga(Ca + Cv \, H)} (T_{x,t} - \theta_{x,t}) \quad (4.2)$$

$$\theta_{x,t+1} - \theta_{x,t} = \frac{h SA (T_{x,t} - \theta_{x,t})}{dp(C_g + C_w M_{x,t})} - \frac{h_{fg} + C_v(T_{x,t} - \theta_{x,t})}{dp(C_p + C_w M_{x,t})} - \frac{Ga}{Dx} (H_{x+1,t} - H_{x,t}) \quad (4.3)$$

$$M_{x,t+1} = \text{Equation (3.7)} \quad (4.4)$$

To determine the internal moisture content and temperature gradients at each Dx location within the cooler, the pellet is divided into n concentric shells. The moisture content and temperature are calculated at $n+1$ points from the center ($r = 0$) to the surface ($r = R$). Given the pellet moisture content and temperature at time t and the equilibrium moisture content and air temperature at $t+Dt$, the model subsequently computes the values of moisture content and temperature at each internal node at time $t+Dt$.

Numerical techniques are also used to solve equations (3.6) and (3.9). Since the equations are similar in form, only the finite-difference form of equation (3.6) is discussed.

Applying the forward-difference formula to the left-hand side term, and the central-difference formula to both terms on the right-hand side of equation (3.6), gives:

$$\frac{M_{i-1,j} - 2M_{i,j} + M_{i+1,j}}{(Dr)^2} + \frac{1}{r} \frac{M_{i+1,j} - M_{i-1,j}}{2 Dr} =$$

$$\frac{1}{D} \frac{M_{i,j+1} - M_{i,j}}{Dt} \quad (4.5)$$

Setting $r = N Dr$ and $a = D Dt/(Dr)^2$, and solving equation (4.5) for $M_{i,j+1}$, gives:

$$M_{i,j+1} = a(1 - \frac{1}{2N})M_{i-1,j} + (1-2a)M_{i,j} + a(1+\frac{1}{2N})M_{i+1,j} \quad (4.6)$$

Setting $b = 1 - 1/2N$ and $c = 1 + 1/2N$, Eqn. 4.6 becomes:

$$M_{i,j+1} = ab M_{i-1,j} + (1-2a) M_{i,j} + ac M_{i+1,j} \quad (4.7)$$

Equation (3.6) is not valid at the center of the pellet because r equals zero. This implies that the $(1/r)(\delta M/\delta r)$ term cannot be determined. However, by l'Hopital's rule (Thomas, 1969), at $r = 0$ the center of a pellet:

$$\lim_{r \rightarrow 0} \left(\frac{1}{r} \frac{\delta M}{\delta r} \right) = \frac{\delta^2 M}{\delta r^2}$$

The moisture-diffusion equation at the location $r=0$ takes the form:

$$2 \frac{\delta^2 M}{\delta r^2} = \frac{1}{D} \frac{\delta M}{\delta t} \quad (4.8)$$

At $i = 0$, equation (4.7) becomes:

$$M_{0,j+1} = ab M_{-1,j} + (1-2a) M_{0,j} + ac M_{1,j} \quad (4.9)$$

Equation (4.9) has a fictitious moisture content $M_{-1,j}$ which can be eliminated by using equation (4.8). Applying the central-difference formula at the left-hand side and the forward-difference formula at the right-hand side, and solving for $M_{-1,j}$ at $i = 0$, results in:

$$M_{-1,j} = \frac{1}{2a} M_{0,j+1} - \frac{1-4a}{2a} M_{0,j} - M_{1,j} \quad (4.10)$$

where $a = D \Delta t / (Dr)^2$.

Substituting equation (4.10) into (4.9) and solving for $M_{0,j+1}$, the moisture content at the center of the pellet becomes:

$$M_{0,j+1} = \frac{1 + 2N - 4a}{1 + 2N} M_{0,j} + \frac{4a}{1 + 2N} M_{1,j} \quad (4.11)$$

where $N = R / Dr$.

At $r = R$ ($i=N$), the surface of the pellet, equation (4.7) becomes:

$$M_{N,j+1} = ab M_{N-1,j} + (1-2a) M_{N,j} + ac M_{N+1,j} \quad (4.12)$$

Equation (4.12) has a fictitious moisture content $M_{N+1,j}$, which can be eliminated by using the convective boundary condition at $r = R$:

$$D \frac{\delta M}{\delta r} + h_d M_s = h_d EMC \quad (3.8)$$

The central-difference formula gives:

$$D \frac{M_{i+1,j} - M_{i-1,j}}{2 Dr} + h_d M_{i,j} = h_d EMC \quad (4.13)$$

At $i = N$ and solving for $M_{N+1,j}$:

$$M_{N+1,j} = M_{N-1,j} - \frac{2 h_d Dr}{D} M_{N,j} + \frac{2 h_d Dr}{D} EMC \quad (4.14)$$

Substituting Equation (4.14) into (4.12) and rearranging, results in:

$$M_{N,j+1} = 2a M_{N-1,j} + (1-2a - \frac{2ac h_d Dr}{D}) M_{N,j} + \frac{2ac h_d Dr}{D} EMC \quad (4.15)$$

Let $d = (2ac h_d Dr) / D$. Thus,

$$M_{N,j+1} = 2a M_{N-1,j} + (1-2a - d) M_{N,j} + d EMC \quad (4.16)$$

The final finite-difference equations for calculation of the moisture content inside a pellet are:

At $r = 0$ ($i=0$), the center of the pellet:

$$M_{0,j+1} = \frac{1 + 2N - 4a}{1 + 2N} M_{0,j} + \frac{4a}{1 + 2N} M_{1,j} \quad (4.11)$$

For $r = Dr$ to $r = R - Dr$ ($i = 1$ to $N - 1$):

$$M_{i,j+1} = ab M_{i-1,j} + (1-2a) M_{i,j} + ac M_{i+1,j} \quad (4.7)$$

At $r = R$ ($i = N$), the surface of the pellet:

$$M_{N,j+1} = 2a M_{N-1,j} + (1-2a-d) M_{N,j} + d EMC \quad (4.16)$$

where: $a = D \Delta t / (\Delta r)^2$

$$b = 1 - 1/2N, \quad c = 1 + 1/2N, \quad d = (2ac h_d \Delta r) / D$$

D = diffusion coefficient, m^2/h

h_d = mass transfer coefficient, m/h .

The initial condition is:

$$M(r,0) = M_j \quad 0 \leq r \leq R \quad (4.17)$$

Following the same procedure as for moisture content, the finite-difference temperature equations inside a pellet can be written.

At $r = 0$ ($i=0$), the center of the pellet:

$$\theta_{0,j+1} = \frac{1 + 2N - 4a}{1 + 2N} \theta_{0,j} + \frac{4a}{1 + 2N} \theta_{1,j} \quad (4.18)$$

For $r = \Delta r$ to $r = R - \Delta r$ ($i = 1$ to $N - 1$):

$$\theta_{i,j+1} = ab \theta_{i-1,j} + (1-2a) \theta_{i,j} + ac \theta_{i+1,j} \quad (4.19)$$

At $r = R$ ($i = N$), the surface of the pellet:

$$\theta_{N,j+1} = 2a \theta_{N-1,j} + (1-2a-d) \theta_{N,j} + d T_{air} \quad (4.20)$$

The initial condition is:

$$\theta(i,0) = \theta_j \quad 0 \leq r \leq R \quad (4.21)$$

where: $a = \alpha \Delta t / (\Delta r)^2$ and $\alpha = K / \rho p C_p$

$$b = 1 - 1/2N, \quad c = 1 + 1/2N, \quad d = (2ac h Dr)/K$$

h = heat transfer coefficient, W/m^2-K

α = thermal diffusivity, W/m^2-J

K = thermal conductivity, $W/m-K$

dp = pellet density, kg/m^3

C_p = specific heat, $J/kg-K$.

At all time steps and locations within the fixed bed the average moisture content and temperature inside the pellets are computed by the following formula:

$$A_{ave} = \frac{A_{o,j} + \sum_{r=1}^N A_{r,j}}{N + 1} \quad (4.22)$$

where: A_{ave} = average moisture content or temperature
 $A_{r,j}$ = moisture content or temperature at each node within the pellet
 N = number of nodes.

In the above calculations, once the α (thermal diffusivity), D (diffusion coefficient), and Dr are fixed, the size of the time step is limited by the following stability criterion (Ozisik, 1980):

$$0 < a = D Dt/(Dr)^2 \leq .5 \quad (4.23)$$

$$0 < a = \alpha Dt/(Dr)^2 \leq .5 \quad (4.24)$$

The three differential equations (4.1), (4.2), (4.3), and the thin-layer drying equation (3.7), along with the moisture content gradient equations (4.7), (4.11), (4.16), (4.17), (4.22), (4.23) and the temperature gradient equations (4.18) to (4.22), and (4.24) constitute the PDE

simulation model for the horizontal-belt pellet cooler. The flow diagram of PDE pellet cooling model is presented in Figure 4.2.

4.3 - Pellet Properties

The pellet properties necessary in the the pellet cooling models are given by;

Equilibrium moisture content (EMC)	Eqns. 3.20,22,23
Diffusion coefficient (D)	Eqn. 3.24
Heat transfer coefficient (h)	Eqn. 3.25
Mass transfer coefficient (h_d)	Eqn. 3.26
Thermal conductivity (K)	Eqn. 3.27
Specific heat (C_p)	Eqn. 3.28
Latent heat of vaporization (h_{fg})	Eqn. 3.29
Pellet bulk density (at MC=20.5 %DB)	673 kg/m ³
Surface area (SA) = $2/R$	

where: R = pellet radius.

The fixed-bed cooling simulation model programs are written in IBM BASICA which runs on IBM PCs and other IBM compatible microcomputers. The programs are compiled with a MICROSOFT BASIC compiler. Each cooling test simulation is performed with a bed depth of 30.48 cm (1 ft).

The HMB and PDE computer programs are presented in Appendices C and D each with a sample run.

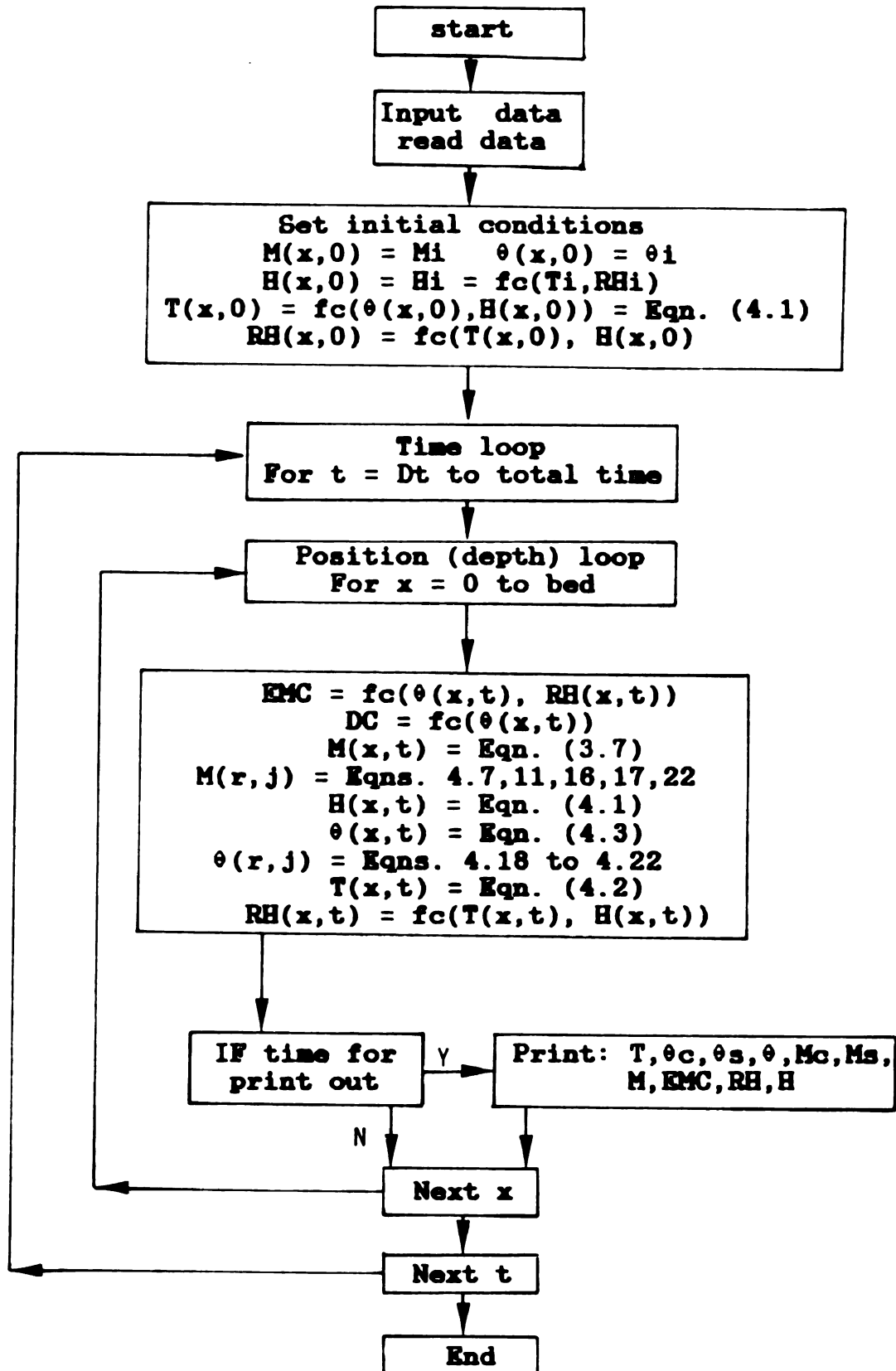


Fig. 4.2 - Flow diagram of the PDE stationary-bed pellet cooling model.

4.4 - Psychrometric Chart Model

The psychrometric model developed in this study for use on the IBM-AT is written in BASICA. It is based on a combination of theoretical and empirical equations presented by Brooker et al. (1974), Chau (1980), and Wilhelm (1976).

The model accepts as input, in English or SI units, the following combination of dry air-water vapor mixture properties: (1) dry-bulb temperature and relative humidity, (2) dry-bulb temperature and absolute humidity, (3) dry-bulb temperature and wet-bulb temperature, (4) dry-bulb temperature and dew-point temperature, (5) wet-bulb temperature and relative humidity, (6) dew-point temperature and relative humidity, and (7) dew-point temperature and enthalpy.

The psychrometric model was developed for use as a subroutine in the drying and cooling simulation models of biological materials. The PSYCHART program is presented in the Appendix B.

5 - EXPERIMENTAL PROCEDURES

The research reported in this study was carried out at the processing laboratory in the Agricultural Engineering Department at Michigan State University.

5.1 - Pellets

The pellets used in this study were obtained from Purina Mills, Lansing, Michigan. The pellet type was Milk Generator # 1000 (B) 16%, with a diameter of 4.76 mm (3/16 in.). The following ingredients are contained according to the company in the pellets: grain products, processed grain by-products, plant protein products, molasses products, vitamins, and minerals. Purina was unwilling to supply the exact composition of the pellets.

The analysis of the pellets indicates that the pellets have at least 16% of protein, 2% of crude fat, and no more than 7.5% of crude fiber. The moisture content of the warm pellets ranged from 18.1 % to 20.7% DB., the temperature after the pellet-mill from 60 C (140 F) to 80 C (176 F).

5.2 - Equipment

Figure 5.1 is the schematic of the equipment used in the deep-bed cooling and drying tests.

The cooling and drying chamber is constructed of sheet metal. It measures 50.8 cm (20 in.) high and 20.32 cm (8 in.) in diameter, and has a volume of .02 m³ (.6 ft³); it is insulated with 2.5 cm (1 in.) of fiber-glass to minimize the effect of temperature fluctuation in the surroundings. At 10.16 cm (4 in.) from the bottom, the chamber is fitted with a wire mesh to hold the bed of pellets. The bed-depth of the cooler is 30.48 cm (12 in.). A series of 4 mm diameter holes were drilled in the cooler wall for the thermocouples probes; an additional set of holes of 2.5 cm (1 in.) diameter enable withdrawal of small samples for moisture determination.

The .22 cubic meter (eight cubic foot) plenum chamber is constructed of plywood.

An Aminco-Aire* air conditioning unit, model 4-5460, was used to deliver air to the drying and cooling chamber. The unit is able to condition a maximum of 8.5 cubic meters per minute (300 CFM); it is designed to condition chambers of less than 1.1 cubic meters (40 cubic feet). About 2.8 cubic meter (100 CFM) of air were required

* Trade names are used solely to provide specific information. Mention of a trade name does not constitute an endorsement by the Agricultural Engineering Department of the Michigan State University of the product nor to the exclusion of other products not mentioned.

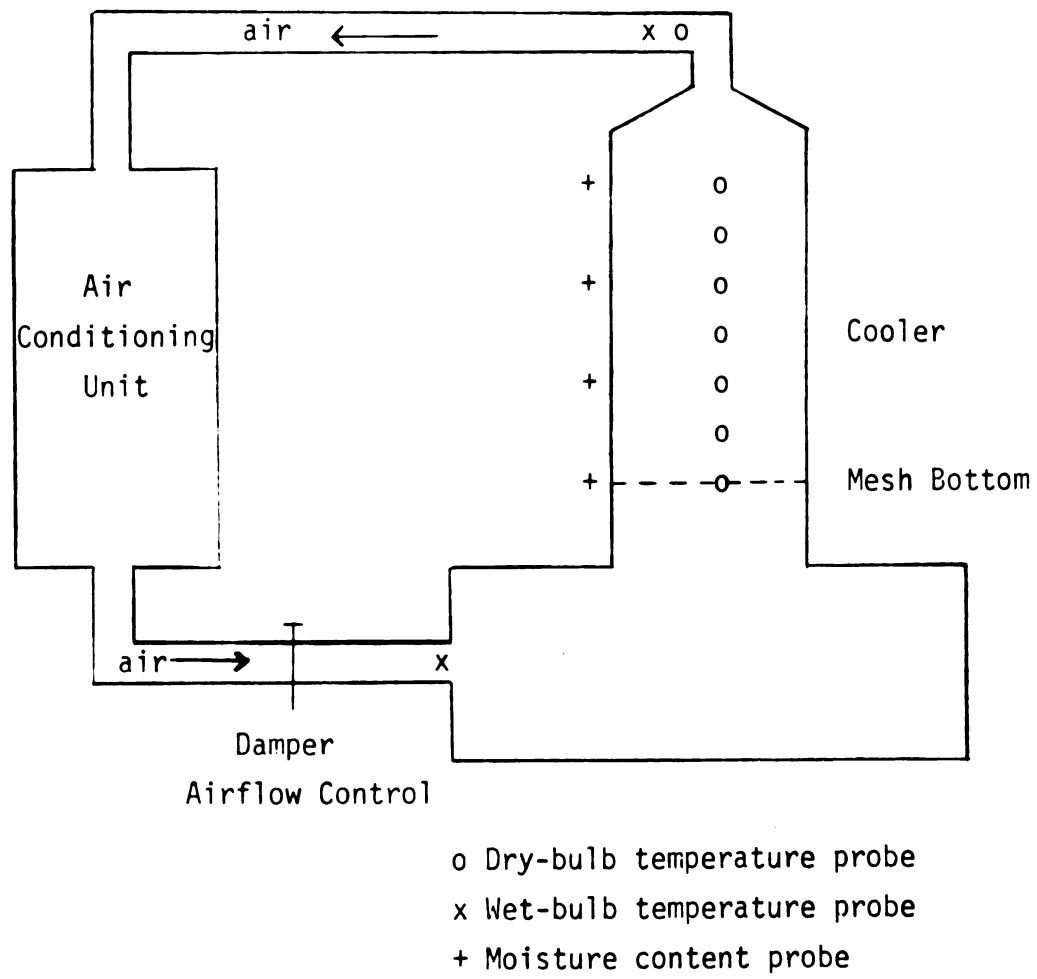


Fig. 5.1 - Fixed-bed cooling experimentation.

in the experiments. The air is conditioned by the Aminco-Aire in two stages. In the first stage, in which the air is washed by a spray of water droplets, the required dew-point temperature is obtained. In the second stage, the air is heated or cooled to the desired dry-bulb temperature.

The solid state controls on the Aminco-Aire unit maintain the dry-bulb temperature and relative humidity of the air to within $\pm .5$ C and $\pm 1\%$, respectively.

The Aminco-Aire unit is connected with a 10.16 cm (4 in.) diameter flexible plastic hose to the plenum chamber of the dryer or cooler. The top of the cooler is connected with a similar plastic hose to the inlet port of the air-conditioning unit. The hoses are insulated with 1.2 cm (.5 in.) of fiber-glass.

5.3 - Single-Layer Tests

The single-layer drying tests were conducted using the Aminco-Aire unit at an airflow of .5 m/s (100 CFM) (Bruce, 1985). The experimental single-layer drying conditions are summarized in Table 5.1.

When the Aminco-Aire conditions had reached the desired air temperature and relative humidity, a single-layer of pellets of approximately 200 g was placed on a wire-mesh tray in the drying chamber. The moisture content

was determined before and after each specified drying time.

The values of the moisture content (as a function of drying time, temperature, and relative humidity) formed the input to the BMDPAR program of the statistical package BMDP (Dixon, 1981). BMDPAR performed the non-linear regression analysis for the estimation of the equilibrium moisture content and diffusion coefficient of the feed pellets.

Table 5.1 - Experimental Single-Layer Drying Conditions for 4.76 mm Diameter Pellets.

Test #	Drying Air Temp. (C)	R.H. (%)	Air Flow (m/s)	Drying Time (Min.)	Initial Mois.Cont. (%DB)
1	15.6	55	.5	1,2,5,10,60	19.1
2	15.6	70	.5	1,2,5,10,60	18.7
3	21.1	40	.5	1,2,5,10,60	18.6
4	21.1	55	.5	1,2,5,10,60	18.1
5	21.1	70	.5	1,2,5,10,60	18.5
6	28.7	40	.5	1,2,5,10,60	18.6
7	28.7	55	.5	1,2,5,10,60	18.2
8	28.7	70	.5	1,2,5,10,60	18.6
9	32.2	40	.5	1,2,5,10,60	18.6
10	32.2	55	.5	1,2,5,10,60	18.5
11	32.2	70	.5	1,2,5,10,60	18.7
12	37.8	40	.5	1,2,5,10,60	18.6
13	37.8	55	.5	1,2,5,10,60	19.1
14	37.8	70	.5	1,2,5,10,60	18.6
15	43.3	40	.5	1,10,60	18.6
16	43.3	55	.5	1,2,5,10,60	19.1
17	43.3	70	.5	10,60	18.6

5.4 - Fixed-Bed Tests

The parameters required for the evaluation of the fixed-bed pellet cooling process are: (1) the pellet inlet moisture content (2) the pellet inlet temperature, (3) the pellet diameter, (4) the pellet density, (5) the cooling air temperature and relative humidity, (6) the air flow, (7) the cooling time, and (8) the bed depth.

The warm pellets were transported from the commercial pellet mill to the MSU laboratory in an insulated box. About 25 Kg (55 lb.) were used to conduct each test.

The hot pellets were poured into the cooler by free-fall from about 30 cm (1 ft) high. Thus, the condition of the pellets is similar to that encountered in commercial horizontal belt coolers. Therefore, the fixed-bed of pellets represents a working section of a cooler with an elapsed time corresponding to the passage time over the length of the cooler belt.

Air velocities of .1 and .5 m/s were tested. the values represent the lower and upper limit of the commercial pellet coolers.

It was assumed that the moisture content and temperature of the pellets were initially uniform throughout the cooler.

The test condition desired in the cooling chamber was maintained for at least one hour before the start of a test. The dry-bulb and wet-bulb temperatures were

continuously monitored; they varied by less than $\pm .5$ C.

Table 5.2 is a summary of the experimental cooling test conditions during the fixed-bed cooling tests. Only the tests for which a complete set of data was collected are used in the evaluation.

Table 5.2 - Experimental Cooling Test Conditions of a 30.48 cm Fixed-Bed of Pellets of 4.76 mm diameter.

Test #	Cooling Air Temp. (C)	R.H. (%)	Air Flow (m/s)	Cooling Time (Min.)	Initial Mois.Cont. (%DB)	Initial Pel.Temp. (C)
1	21.1	55	.5	10,15,20	20.7	71.6
2	21.1	55	.1	15	20.7	65.6
3	26.7	55	.5	10,15,20	20.5	62.8
4	26.7	55	.1	15	20.5	58.5
5	32.2	55	.5	10,15,20	19.1	72.7
6	32.2	55	.1	15,20	19.1	67.2
7	17.7	70	.5	10,15,20	19.6	69.4
8	17.7	70	.1	15,20	19.6	61.7
9	21.1	70	.5	10,15,20	19.8	71.1
10	21.1	70	.1	15,20	19.8	63.3
11	26.7	70	.5	10,15,20	20.5	65.6
12	26.7	70	.1	15	20.5	60.0
13	21.1	55	.1	10,15,20	18.1	69.3
14	21.1	55	.5	15	18.1	63.4

5.5 - Instrumentation

The following parameters required measurement for the performance evaluation of a pellet cooler: (1) air velocity, (2) air temperature, (3) relative humidity, (4) pellet temperature, (5) initial and final moisture contents, and (6) pellet densities.

Air Flow:

The air flow across the pellets was controlled by a manually adjustable damper located in the duct to the plenum chamber. It was measured by a Weathertronics hot-wire anemometer model 2440, with an accuracy of ± 0.05 m/s.

Temperature:

The temperatures (dry- and wet-bulb) were measured with copper constantan thermocouples and recorded every minute with a Ramp/Processor (Kaye Instruments) data logger. A total of 11 thermocouples monitored the temperatures of the inlet air (dry- and wet-bulb), the exhaust air (dry and wet-bulb), and at seven selected points between the pellets within the cooler. The accuracy of the temperature measurement is ± 0.5 C.

Relative Humidity:

The relative humidity was controlled automatically by the air conditioning unit and measured by dry- and wet-bulb copper constantan thermocouples located at the inlet of the cooler. The accuracy of the relative humidity measurements is $\pm 1\%$.

Moisture Content:

The initial moisture content was obtained by sampling the warm pellets. After the cooling was completed four samples were collected at the locations indicated in Figure 5.1.

The moisture content of the pellets was determined by drying triplicate samples for 24 hours in an air oven at 103 C according to ASAE Standards (1984b). The samples were cooled in a desiccator before reweighing. The accuracy of the moisture content measurement is $\pm .2\%$.

Pellet Densities:

The pellet bulk density was obtained by weighing a container of known volume filled with pellets. A scale with an accuracy of $\pm .03$ Kg was used to weigh the container.

The individual pellet density was determined by the ratio weight/volume of a single pellets. A PAV digital caliper with an accuracy of $\pm .001$ mm was used to measure the pellet length and diameter. The pellet weight was measured with a analytical scale with an accuracy of $\pm .001$ g.

6 - RESULTS AND DISCUSSION

In this chapter the experimental results of the thin-layer drying and of the fixed-bed cooling tests are presented. Also, the experimental and simulated results of the deep-bed cooling tests are compared. Subsequently, the simulation models are used to predict the pellet temperature and the pellet cooling rate under different conditions.

6.1 - Thin-Layer Drying Tests

The drying experimental data of 18% to 19% DB moisture content milk pellets obtained during thin-layer drying at constant temperature and relative humidity are shown in Table 6.1a and Table 6.1b. The air velocity during the experiments was .5 m/s. The drying air temperature ranged from 15.6 to 43.3 C (60 to 110 F), the relative humidity between 40 and 70%.

Table 6.1a - Experimental and Predicted Pellet Moisture Content (%DB) as a Function of Temperature, Relative Humidity and Time. Experimental Data Obtained in Thin-Layer Pellet Drying Tests.

Time (min)	Temperature (C)					
	15.6		21.1		26.7	
	Obs.	Pred.*	Obs.	Pred.	Obs.	Pred.
Relative Humidity = 40%						
0.0	-	18.6	18.6	18.6	18.6	18.6
1.0	-	17.9	18.0	17.8	18.0	17.7
2.0	-	17.6	17.8	17.5	17.7	17.3
5.0	-	17.1	17.2	16.8	17.2	16.6
10.0	-	16.6	16.5	16.2	16.3	15.9
60.0	-	14.6	13.5	13.9	12.8	13.3
180.0	-	13.9	-	13.2	-	12.6
Relative Humidity = 55%						
0.0	19.2	19.2	18.1	18.1	18.2	18.2
1.0	18.7	18.7	17.9	17.6	17.5	17.6
2.0	18.5	18.5	17.6	17.5	17.5	17.4
5.0	18.3	18.1	17.4	17.1	17.1	16.9
10.0	17.7	17.7	17.2	16.7	16.6	16.5
60.0	16.5	16.2	15.8	15.4	14.9	14.8
180.0	-	15.7	-	15.0	-	14.4
Relative Humidity = 70%						
0.0	18.7	18.7	18.5	18.5	18.6	18.6
1.0	18.4	18.6	18.4	18.3	18.2	18.3
2.0	18.4	18.5	18.4	18.2	18.0	18.2
5.0	18.2	18.5	18.3	18.1	17.9	17.9
10.0	17.9	18.4	18.1	17.9	17.7	17.7
60.0	16.9	18.0	16.6	17.3	16.4	16.8
180.0	-	17.9	-	17.2	-	16.5

Milk pellet 16% protein; diameter = 4.76 mm. (3/16 in.)

Assumed that equilibrium has been reached after 60 minutes.

Airflow rate = .5 m/s

Pellet density = 945 Kg/m³

Pellet bulk density (at MC = 20.5 %DB) = 673 Kg/m³

* Predicted values obtained using Eqns. (6.1), (6.2), (6.5) and (6.6).

Table 6.1b - Experimental and Predicted Pellet Moisture Content (%DB) as a Function of Temperature, Relative Humidity and Time. Experimental Data Obtained in Thin-Layer Pellet Drying Tests.

Time (min)	Temperature (C)					
	32.2		37.8		43.3	
	Obs.	Pred.*	Obs.	Pred.	Obs.	Pred.
Relative Humidity = 40%						
0.0	18.6	18.6	18.6	18.6	18.6	18.6
1.0	18.2	17.6	18.2	17.5	17.8	17.4
2.0	17.7	17.2	17.7	17.1	-	16.9
5.0	16.8	16.4	16.7	16.2	-	16.1
10.0	15.7	15.6	15.6	15.4	14.7	15.1
60.0	11.7	12.8	11.4	12.3	10.3	11.9
180.0	-	12.0	-	11.5	-	11.1
Relative Humidity = 55%						
0.0	18.5	18.5	19.1	19.1	19.1	19.1
1.0	17.8	17.7	18.7	18.2	18.4	18.1
2.0	17.5	17.5	18.4	17.8	18.2	17.7
5.0	17.5	16.9	17.6	17.2	17.3	17.0
10.0	16.6	16.4	16.7	16.5	16.2	16.2
60.0	14.5	14.4	13.8	13.9	12.7	13.5
180.0	-	13.8	-	13.4	-	12.9
Relative Humidity = 70%						
0.0	18.7	18.7	18.6	18.6	18.5	18.5
1.0	18.6	18.3	18.5	18.1	-	17.9
2.0	18.5	18.1	18.4	17.9	-	17.7
5.0	17.8	17.8	17.5	17.6	-	17.3
10.0	17.4	17.5	17.2	17.2	17.8	16.9
60.0	16.0	16.3	15.9	15.8	15.7	15.4
180.0	-	16.0	-	15.5	-	15.1

Milk pellet 16% protein; diameter = 4.76 mm. (3/16 in.)

Assumed that equilibrium has been reached after 60 minutes.

Airflow rate = .5 m/s

Pellet density = 945 Kg/m³

Pellet bulk density (at MC = 20.5 %DB) = 673 Kg/m³

* Predicted values obtained using Eqns. (6.1), (6.2), (6.5) and (6.6).

6.1.1 - Equilibrium Moisture Content and Diffusion Coefficient

The program BMDPAR, contained in the BMDP statistical software package of Dixon (1981), was used in the statistical analysis to fit a nonlinear model to the experimental thin-layer drying data shown in Tables 6.1a and 6.1b, and to estimate the constants in the EMC and D equations.

In the first step, the data is fitted to Equation (3.7) (in which it is assumed that $h_d = \infty$), using three exponentials terms to estimate the values of the equilibrium moisture content (EMC) and the diffusion coefficient (D) at the same time (Byler, 1983). Assuming that $h_d = \infty$ Equation (3.7) can be then written in the following form:

$$M_t = EMC + (M_i - EMC) * (A * \exp(-k_1 * D * t) + (B * \exp(-k_2 * D * t) + (C * \exp(-k_3 * D * t))) \quad (6.1)$$

where: M_t = Moisture content at time t (decimal DB)
 M_i = Initial moisture content (decimal DB)
 EMC = Equilibrium moisture content (decimal DB)
 D = Diffusion coefficient (m^2/h)
 t = Time (hour)

$$A = 4/(\alpha_1)^2 \quad B = 4/(\alpha_2)^2 \quad C = 4/(\alpha_3)^2$$

$$k_1 = (\alpha_1)^2/R^2 \quad k_2 = (\alpha_2)^2/R^2 \quad k_3 = (\alpha_3)^2/R^2$$

α_n = Roots of the Bessel function of zero order
 given by Churchill and Brown (1978)

$$\alpha_1 = 2.405 \quad \alpha_2 = 5.52 \quad \alpha_3 = 8.654$$

A subroutine EMCD, presented in Appendix E, was written in FORTRAN using Equation 6.1 with EMC and D as parameters to be estimated for each combination of temperature and relative humidity (five points, the moisture contents at time zero were excluded) listed in Tables 6.1a and 6.1b. The results showed that the EMC and D are highly correlated, (correlation coefficient = .9997). Therefore, it is impossible to estimate EMC and D simultaneously and accurately (Beck, 1986). Hence, one parameter has to be fixed to estimate the other.

It was assumed that equilibrium has been reached after 60 minutes of drying time. Thus, the observed values of the moisture content (decimal) in Tables 6.1a and 6.1b at 60 minutes (17 points) can be employed as EMC data in the BMDPAR program for the estimation of the parameters in the Nellist (Eqn.3.20), Henderson (Eqn. 3.22), and Chung-Pfost (Eqn. 3.23) EMC equations. The parameter values, with the asymptotic standard deviation, the residual sum of squares and the mean relative deviation modulus (P) are presented in Table 6.2.

The goodness of fit of the equations can be evaluated from: (1) the mean relative deviation modulus (P) (defined by Equation 3.40). A P value of less than or equal to 5 means that the equation is a good fit (Lomauro, 1985); the equation with the smallest P value is considered the best fit. All three EMC equations gave P values less than 5; thus the equations can be considered a good fit. (2) the residual sum of squares ($\sum R^2$). The equation with the

smallest value of ER^2 is considered the best fit. The Chung-Pfost EMC equation resulted in the smallest P and residual sum of squares values.

Table 6.2 - Constants and Statistical Data Obtained by Regression Analysis of the Equilibrium Moisture Content Data*** in Tables 6.1a and 6.1b.

EMC Equations	Constants	Asymptotic St Deviation	P*	ER^2 **
Nellist	a	.191	3.40	5.906E-04
	b	.055		
	c	.028		
Henderson	a	6.66	3.44	5.750E-04
	b	22.12		
	c	3.11		
Chung-Pfost	a	.277	3.13	4.898E-04
	b	.042		
	c	13.3		

* P = Mean relative deviation modulus

** ER^2 = Residual sum of squares

*** EMC is assumed to be the moisture content reached after 60 minutes of drying.

The observed and predicted values of the EMC in the three equations are presented in Table 6.3. Figure 6.1 shows the observed and predicted values at 55% relative humidity; there is acceptable agreement between the two sets of values.

The predicted EMC values are also in good agreement with the experimental data shown in Table 3.9 obtained by Headley (1969). For example, at 21.1 C and 55% relative humidity, Headley's values range from 13.6 to 15.9 %DB compared to the predicted EMC value of 15.0 %DB from the Chung-Pfost equation.

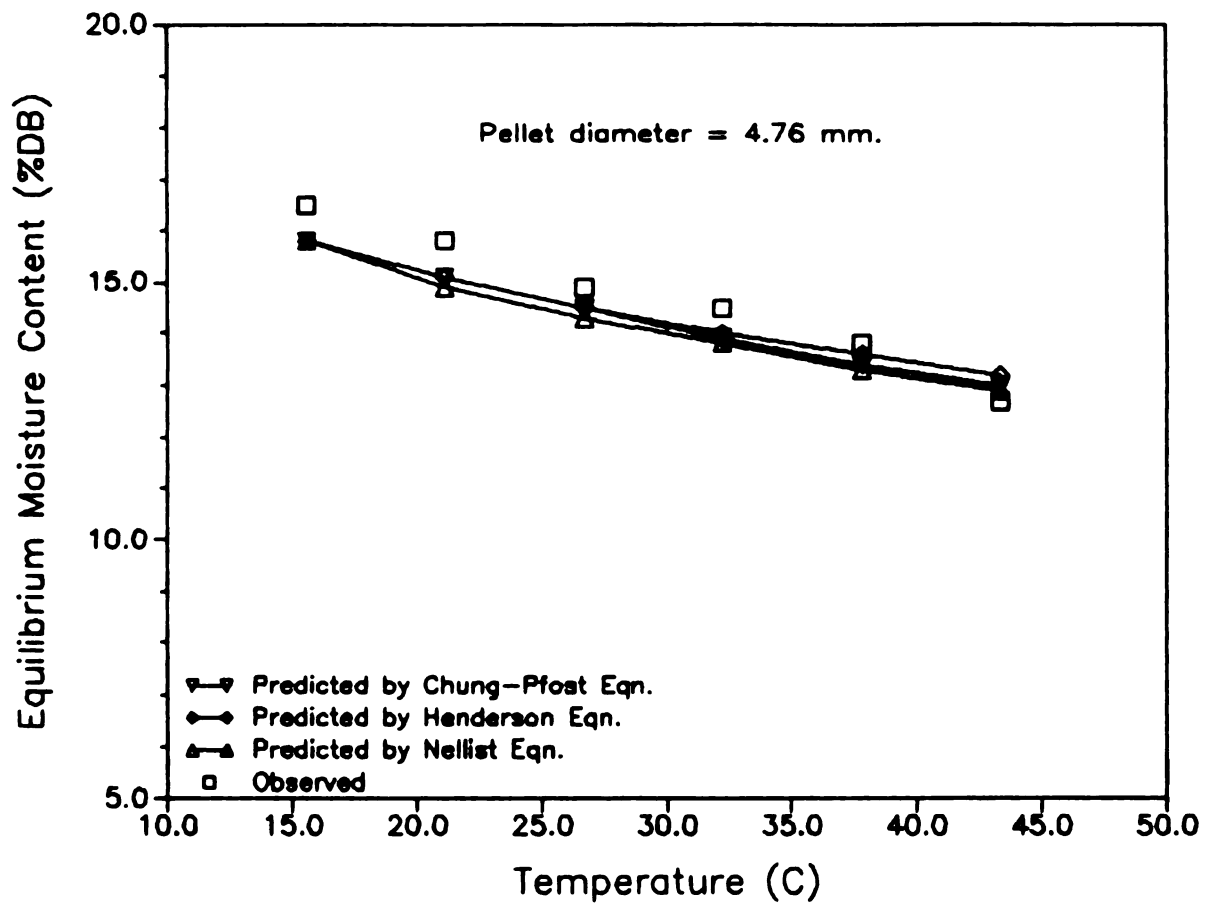


Fig. 6.1 Observed and predicted equilibrium moisture content. Relative humidity 55%.

Table 6.3 - Observed and Predicted Values of the Equilibrium Moisture Content (%DB) of Feed Pellets.

Temp. (C)	Observed	Predicted by Nellist	Henderson	Equations Chung-Pfost
Relative Humidity = 40%				
21.1	13.5	13.4	13.0	13.2
26.7	12.8	12.7	12.5	12.6
32.2	11.7	12.2	12.1	12.0
37.8	11.4	11.7	11.7	11.5
43.3	10.3	11.4	11.4	11.1
Relative Humidity = 55%				
15.6	16.5	15.8	15.7	15.7
21.1	15.8	15.0	15.1	15.0
26.7	14.9	14.3	14.5	14.4
32.2	14.5	13.8	14.0	13.8
37.8	13.8	13.3	13.6	13.3
43.3	12.7	12.9	13.2	12.9
Relative Humidity = 70%				
15.6	16.9	18.0	18.0	17.9
21.1	16.6	17.2	17.2	17.2
26.7	16.4	16.5	16.5	16.5
32.2	16.0	16.0	16.0	16.0
37.8	15.9	15.6	15.5	15.5
43.3	15.7	15.2	15.0	15.1

The plots of the residuals of the three EMC equations were examined. Figure 6.2 shows the residuals of the Chung-Pfost Equation plotted against the predicted equilibrium moisture content. Instead of being randomly distributed around the y-axis, the residuals form a systematic pattern, which implies that the parameters in the equation are correlated (Beck and Arnold, 1977). The other two EMC equations showed similar pattern.

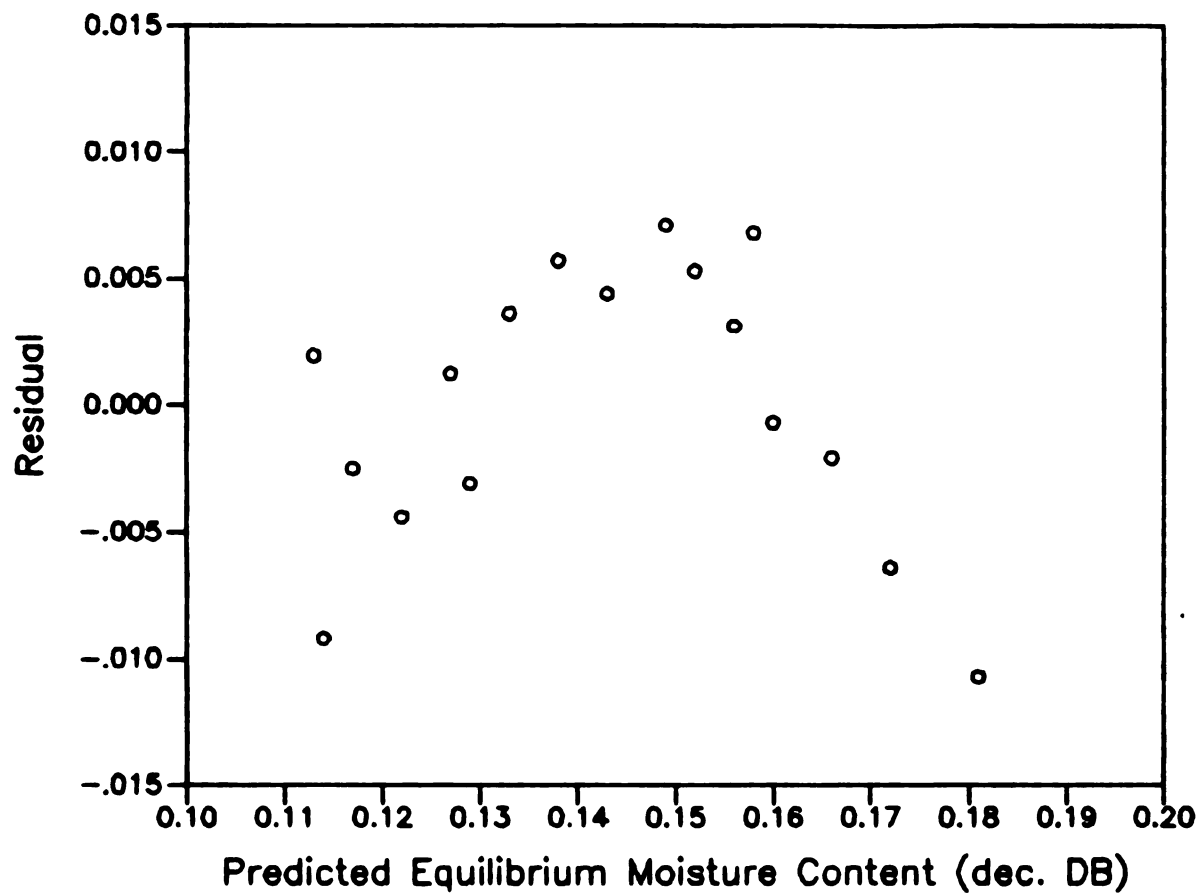


Fig. 6.2 Residuals of equilibrium moisture content for Chung-Pfost EMC equation.

With the experimental EMC values known (see the 60 minutes data in Tables 6.1a and 6.1b), the D values can be determined at each of the six temperatures (it is assumed that D is only a function of temperature). Equation (6.1) is used for time > 2 minutes, and the following equation is employed for time ≤ 2 minutes (Crank, 1975):

$$\frac{M_t}{M_\infty} = \frac{4}{\pi^{1/2}} \left(\frac{D t}{R^2} \right)^{1/2} - \frac{D t}{R^2} - \frac{1}{3\pi^{1/2}} \left(\frac{D t}{R^2} \right)^{3/2} + \dots \quad (6.2)$$

where: M_t = moisture content at time t (decimal DB)
 M_∞ = moisture content after infinite time (dec DB)
 D = diffusion coefficient (m^2/h)
 R = pellet radius (m)
 t = time (hour)

Figure 6.3 shows the values of D (with asymptotic standard deviation varying from 2.00E-07 to 2.65E-07) found with Equations (6.1) and (6.2). These D values were subsequently employed to determine the parameters a and b in the Arrhenius equation (3.24); the results were: a = 1.015E-05 and b = 547, with asymptotic standard deviations of .1E-06 and 301, respectively. The analysis of the residuals showed that the parameters are correlated. (Figure 6.3 shows the five individual D values determined with the BMDPAR program along with the values predicted by the Arrhenius equation. The high value of D at 26.7 C appears to be due to experimental error).

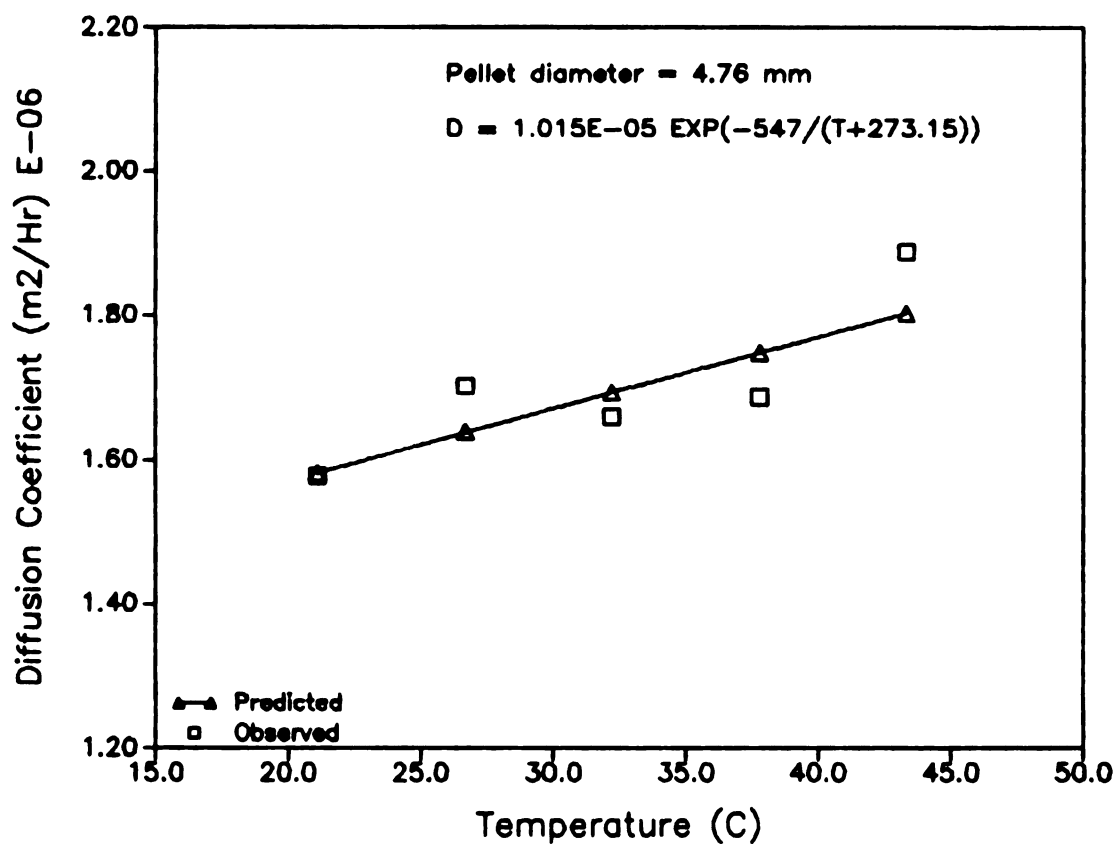


Fig. 6.3 Determined and predicted diffusion coefficients as a function of temperature.

The resulting equations for the EMC of feed pellets are:

Nellist Equation (Eqn. 3.20):

$$\text{EMC} = .191 - .055 \cdot \ln(1 - \text{RH}) - .028 \cdot \ln(\theta) \quad (6.3)$$

Henderson Equation (Eqn. 3.22):

$$\text{EMC} = (-\ln(1 - \text{RH}) / (6.66 \cdot (\theta + 22.12)))^{(1/3.11)} \quad (6.4)$$

Chung-Pfost Equation (Eqn. 3.23):

$$\text{EMC} = .277 - .042 \cdot \ln(-(\theta + 13.3) \cdot \ln(\text{RH})) \quad (6.5)$$

The resulting equation for the diffusion coefficient is (Eqn. 3.24):

$$D = 1.015 \text{E-}05 \cdot \text{EXP}(-547 / (\theta + 273.15)) \quad (6.6)$$

assuming that Equation (3.6) in cylindrical form is used in the temperature range 15.6 to 43.3 C.

In Equations (6.3) to (6.6):

θ = Average pellet temperature (C) and
 RH = Relative humidity (decimal).

The use of equations 6.3 to 6.6 is limited to the temperature range of 15.6 C to 43.3 C, the relative humidity range from 40% to 70%, for pellets with a density of 673 kg/m³ and a chemical analysis as given on page 82.

The analysis of the residuals shows that the parameters in the EMC and D equations are correlated. This seems to imply that the pellets did not reach equilibrium after 60 minutes of drying. This is confirmed in Tables 6.1a and 6.1b (compare the predicted values at 60 minutes of drying with the predicted values at 180 minutes of drying). In the opinion of the author, the correlation of the

parameters in the EMC and D equations does not introduce a serious error in the analysis.

Finally, close analysis of the results shows that in the 15.6 to 43.3 C range the variation in D is so small that use of an average value of D may suffice. This is confirmed by comparing the data in Table 6.4, obtained with a constant D in Equation (6.1), with that in Tables 6.1a and 6.1b.

Table 6.4 - Predicted Pellet Moisture Content (%DB) using a constant Diffusion Coefficient = $1.66 \times 10^{-6} \text{ m}^2/\text{h}$.

Time (min)	15.6	21.1	Temperature (C)				4.33
			26.7	32.2	37.8		
Relative Humidity = 40%							
0.0	18.6	18.6	18.6	18.6	18.6		18.6
1.0	17.8	17.7	17.6	17.6	17.5		17.4
2.0	17.6	17.4	17.3	17.2	17.1		17.0
5.0	17.1	16.8	16.6	16.4	16.3		16.1
10.0	16.5	16.2	15.9	15.6	15.4		15.2
60.0	14.5	13.8	13.3	12.8	12.4		12.0
180.0	13.9	13.2	12.6	12.1	11.5		11.1
Relative Humidity = 55%							
0.0	19.2	18.1	18.2	18.5	19.1		19.1
1.0	18.6	17.6	17.6	17.7	18.2		18.1
2.0	18.5	17.4	17.4	17.5	17.8		17.8
5.0	18.1	17.1	16.9	16.9	17.2		17.1
10.0	17.6	16.7	16.5	16.4	16.5		16.3
60.0	16.2	15.4	14.8	14.4	14.1		13.6
180.0	15.7	15.0	14.4	13.8	13.4		12.9
Relative Humidity = 70%							
0.0	18.7	18.5	18.6	18.7	18.6		18.5
1.0	18.6	18.3	18.3	18.3	18.1		17.9
2.0	18.5	18.2	18.2	18.1	17.9		17.7
5.0	18.4	18.1	17.9	17.8	17.6		17.4
10.0	18.3	17.9	17.7	17.5	17.2		16.9
60.0	18.0	17.3	16.8	16.3	15.9		15.5
180.0	17.9	17.2	16.5	16.0	15.5		15.1

6.2 - Deep-Bed Cooling Tests

The objective of these experiments was to study the effect of cooling air temperature, relative humidity, and velocity on the pellet temperature and moisture content during the fixed-bed cooling process.

A major problem encountered in the study of pellet cooling is the extreme variation in the additives used in formulating a livestock feed. The frequent change in price and availability of the different ingredients greatly affects the formulation of a feed. This change influences the amount of steam and liquid added to the mash during the pelleting process. This in turn results in different temperatures and moisture contents of the pellets. The change in formulation also affects the pellet properties such as the diffusion and mass transfer coefficients, the density, the thermal conductivity, the specific heat, etc.

Tables 6.5 and 6.6 show typical temperature data of deep-bed pellet cooling tests. The results correspond to the conditions of test numbers 3 and 4 shown in Table 5.2. The results of the other tests are presented in Appendix A. In test number 3 (Table 6.4) the pellets cooled from 63 C to an average temperature of 24.6 C after 20 minutes at an air velocity of .5 m/s. (The average temperature is defined as the sum of the thermocouple readings divided by the number of thermocouples within the bed of pellets after 20 minutes of cooling).

The data of Table 6.5 is plotted in Figure 6.4. Due to evaporative cooling, the pellet temperatures at the centre and top of the bed after 11 minutes cooling time are lower than the cooling air temperature.

Table 6.5 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 26.7 C, RH 55%, Air Velocity .5 m/s. Test #3.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	61.7	62.6	63.8	63.4	63.4	62.9	63.2
1	32.6	43.9	47.8	50.7	52.8	53.9	55.2
2	31.4	37.7	41.8	44.0	45.8	47.0	48.2
3	30.1	33.6	37.4	39.4	40.7	42.1	43.1
4	28.9	30.9	34.1	36.1	37.3	38.6	39.4
5	28.1	28.9	31.4	33.4	34.7	35.8	36.7
6	27.6	27.7	29.4	31.2	32.4	33.4	34.3
7	27.5	26.9	28.0	29.4	30.6	31.6	32.4
8	27.4	26.4	26.9	28.1	29.1	30.0	30.8
9	27.3	26.1	26.1	27.1	27.9	28.7	29.5
10	27.3	25.9	25.6	26.2	26.9	27.7	28.3
11	27.3	25.8	25.2	25.6	26.1	26.7	27.3
12	27.3	25.8	25.0	25.1	25.4	26.0	26.6
13	27.3	25.8	24.8	24.7	24.9	25.4	25.9
14	27.3	25.7	24.7	24.3	24.5	24.8	25.3
15	27.2	25.8	24.7	24.2	24.2	24.6	24.9
16	27.2	25.8	24.6	24.1	23.9	24.2	24.5
17	27.3	25.9	24.6	23.9	23.8	23.9	24.2
18	27.3	25.9	24.6	23.8	23.7	23.7	23.9
19	27.3	25.9	24.6	23.8	23.6	23.6	23.7
20	27.3	25.9	24.7	23.9	23.4	23.4	23.5

Initial moisture content = 20.5 %DB
Pellet diameter = 4.76 mm, Pellet density 945 Kg/m³
Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

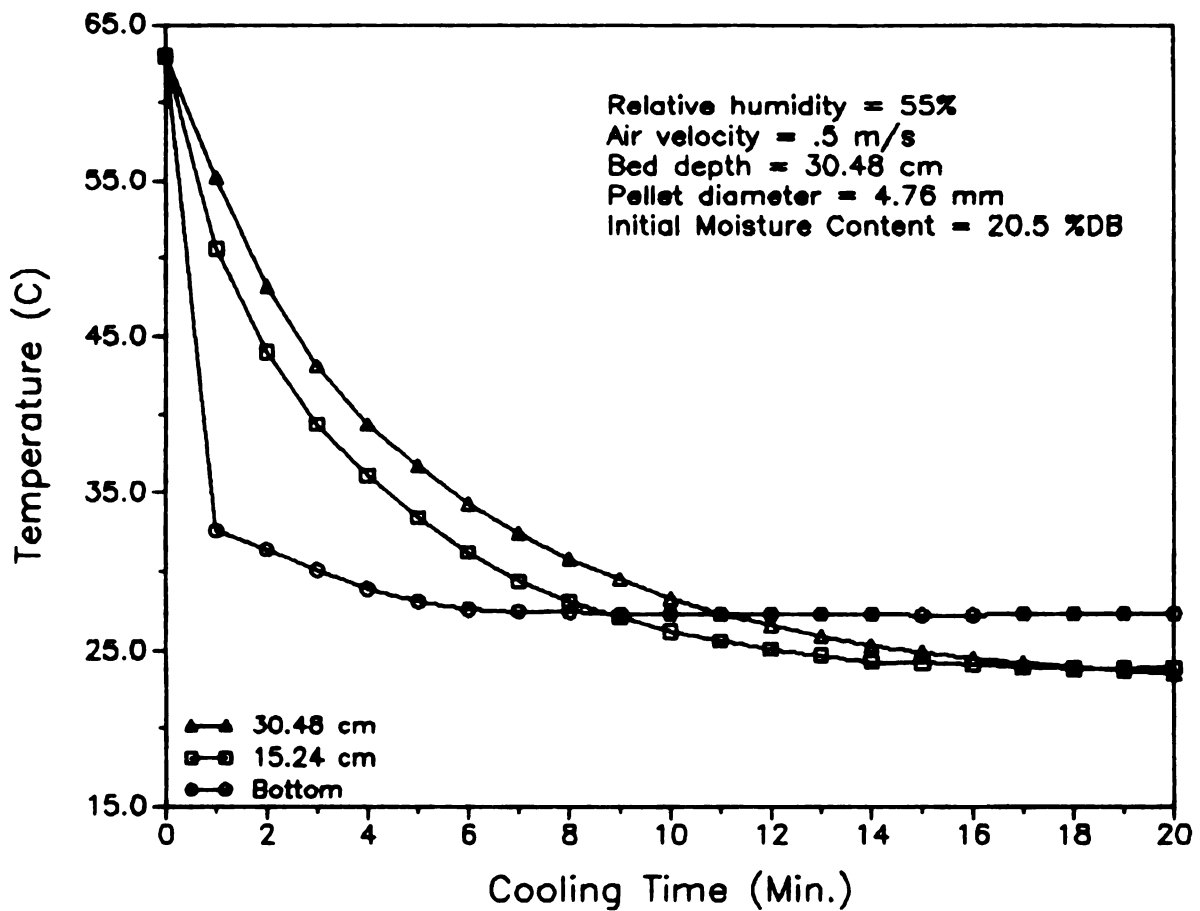


Fig. 6.4 Effect of cooling time on the observed temperatures of a fixed bed of pellets at three bed depths. Cooling air temperature 26.7 C.

Table 6.6 shows the results of test 4. The pellets in this test were cooled at an airflow rate of .1 m/s from 58.5 C to an average temperature 27 C in 15 minutes.

The moisture contents in a bed of pellets after cooling are presented in Table 6.7 for tests 3 and 4. (The average moisture content is the sum of the moisture content measured in four different positions within the bed divided by four).

In test number 3, pellets were dried from an initial moisture content of 20.5 % dry basis to an average moisture content of 17.3 %DB after 20 minutes cooling with air velocity of .5 m/s. There was no change in the average moisture content at .1 m/s (test 4). These results show a deviation from the expected trend. In the cooling and drying of pellets the heat necessary to evaporate liquid is supplied by the pellets, which is not the case in conventional drying where the heat comes from the airstream. Therefore, the initial heat content of the product limits the amount of moisture which can be removed. It was expected that rapid cooling, high air velocity, would reduce moisture content less than low air rates.

Figure 6.5 shows the moisture content within a stationary bed of pellets after three cooling periods at a cooling air temperature of 26.7 C and an air velocity .5 m/s. Longer cooler times results in lower moisture contents.

Table 6.6 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 26.7 C, RH 55%, Air Velocity .1 m/s. Test 4.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	56.7	58.6	56.9	58.6	58.7	61.6	58.7
1	31.3	44.8	48.1	52.7	54.9	56.1	56.5
2	29.8	39.1	42.2	47.1	50.6	53.3	55.1
3	29.0	35.8	38.6	42.7	46.2	49.5	51.6
4	28.3	33.4	35.9	39.4	42.5	45.8	48.1
5	27.8	31.7	33.9	36.9	39.6	42.7	44.9
6	27.4	30.2	32.3	35.0	37.4	40.3	42.4
7	27.2	29.2	30.9	33.3	35.4	38.1	40.1
8	26.9	28.1	29.7	31.9	33.8	36.2	38.1
9	26.7	27.3	28.8	30.7	32.4	34.6	36.3
10	26.7	26.7	28.0	29.7	31.2	33.3	34.9
11	26.4	26.2	27.2	28.8	30.2	32.1	33.6
12	26.4	25.8	26.7	28.1	29.3	31.1	32.4
13	26.4	25.4	26.1	27.4	28.5	30.1	31.5
14	26.3	25.2	25.8	26.9	27.9	29.3	30.6
15	26.3	25.0	25.5	26.5	27.3	28.7	29.9

Initial moisture content = 20.5 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Table 6.7 - Experimental Values of Moisture Content (%DB) within a Fixed-Bed of Pellets Cooled at Two Airflow Rates. Air Temperature 26.7 C, RH 55%.

Cooler Depth (cm)	Air Velocity = .5 m/s			.1 m/s	
	Cooling Time (min)		20	(min)	
	10	15		15	
Bottom	18.3	17.7	17.2	18.3	
10.16	17.7	17.5	17.3	18.1	
20.32	17.7	17.5	17.4	18.2	
30.48	17.9	17.7	17.5	18.5	
Average	17.9	17.6	17.3	18.3	

Initial moisture content = 20.5 %DB

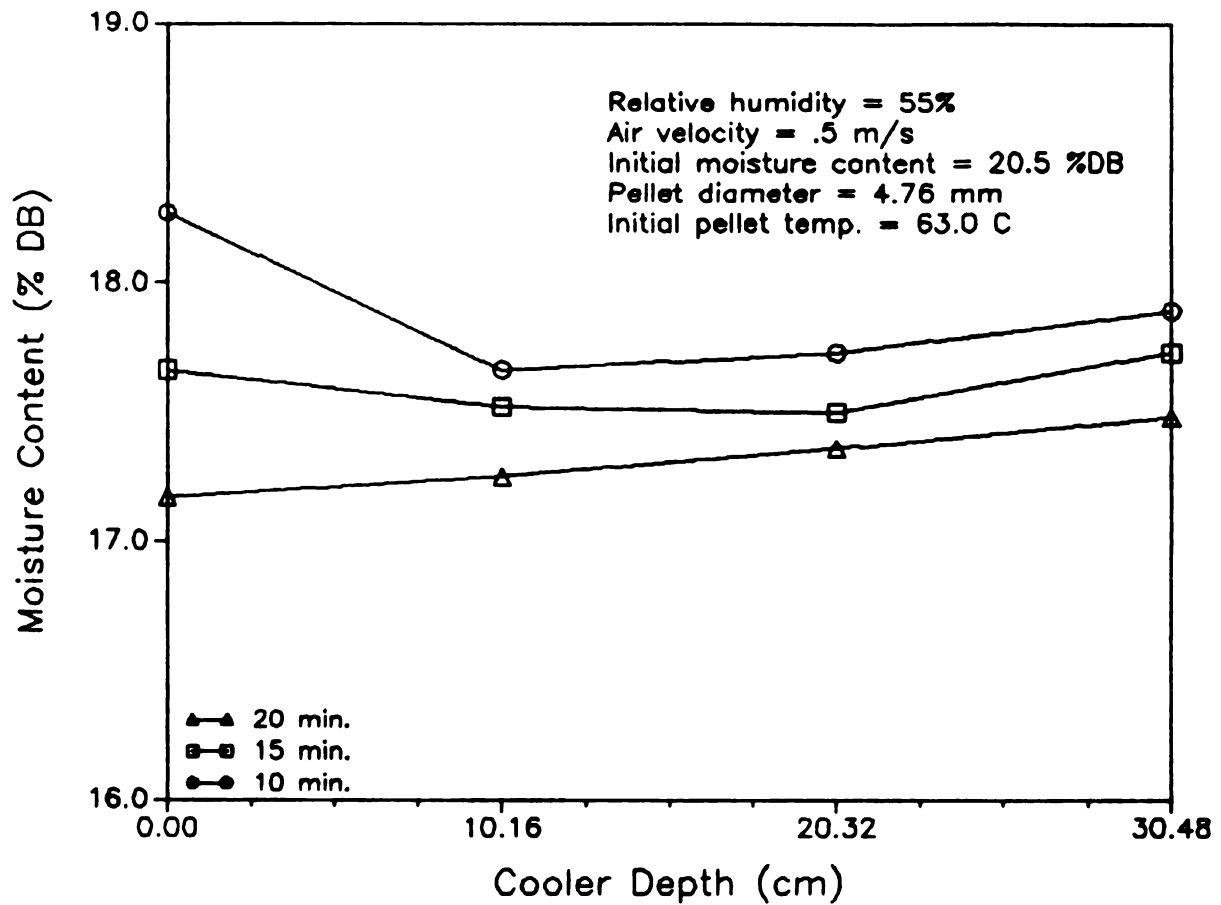


Fig. 6.5 Effect of cooling time on the observed moisture content of a fixed bed of pellets after 20,15,10 min. of cooling. Cooling air temp.26.7 C.

Figure 6.6 shows the effect of cooling air temperature on the observed pellet temperature at the top of a fixed-bed. As expected, a lower cooling air temperature results in a cooler pellet temperature. The effects of cooling air temperature on the moisture content within the bed after 20 minutes cooling is depicted in Figure 6.7. Higher temperatures allow the pellets to approach the ambient conditions more rapidly, but results in lower pellet moisture contents.

Figures 6.8 to 6.11 depict the effect of air velocity on temperature and moisture content of a fixed bed of pellets for two different cooling air temperatures, 26.7 and 32.2 C. The lower airflow produced the warmer pellets, although the pellets had a higher moisture content. The differences between the values for temperature and moisture content for different airflows were smaller for the higher (32.2 C) cooling air temperature.

The effects of relative humidity on temperature at the top of a fixed-bed of pellets and on the moisture content within the bed are presented in Figures 6.12 and 6.13. The pellet temperatures were somewhat higher, about 5 C, for the 70% relative humidities. However, the moisture content at the bottom of the bed was 2% higher which is significant (see Figure 6.13). Since, the temperatures were high at the top of the bed, the moisture content was lower for the 70% relative humidity test.

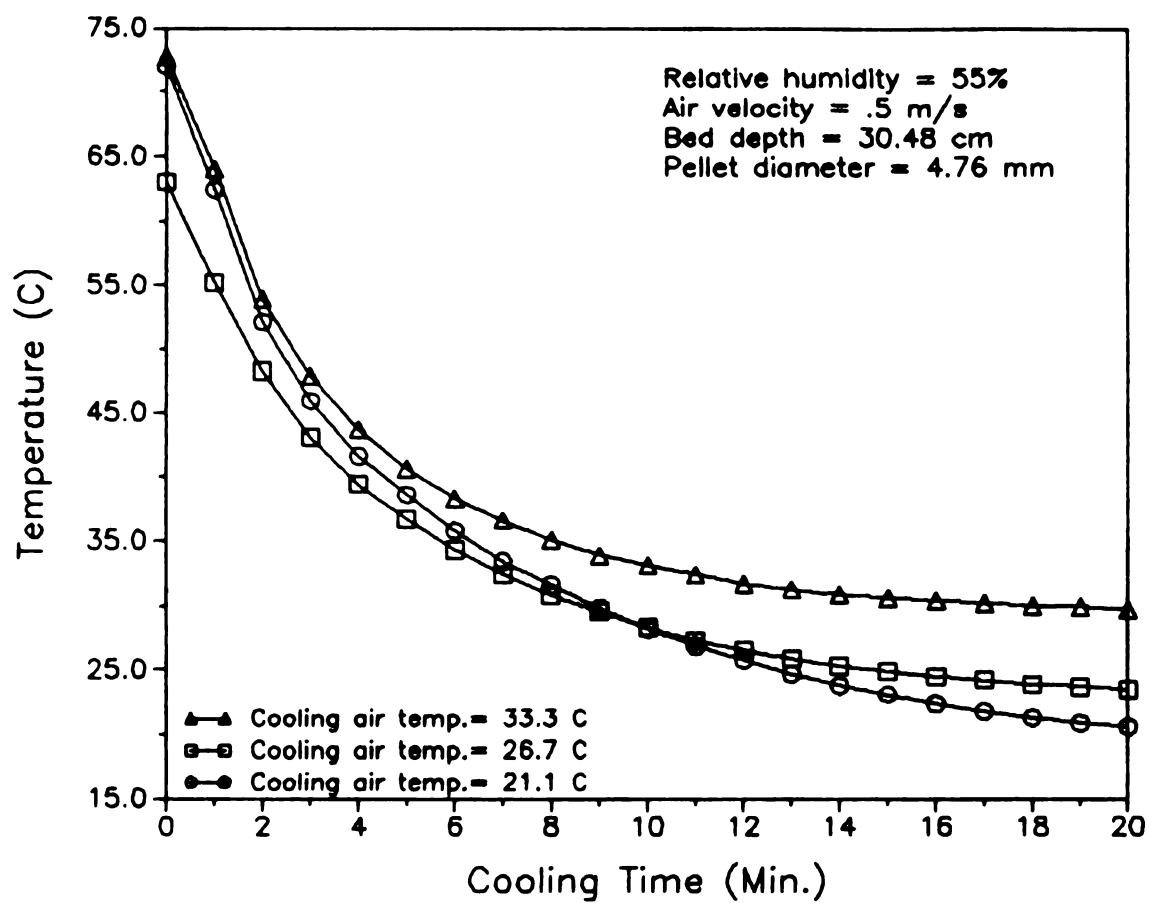


Fig. 6.6 Effect of cooling air temperatures on the observed temperatures at the top of a fixed bed of pellets.

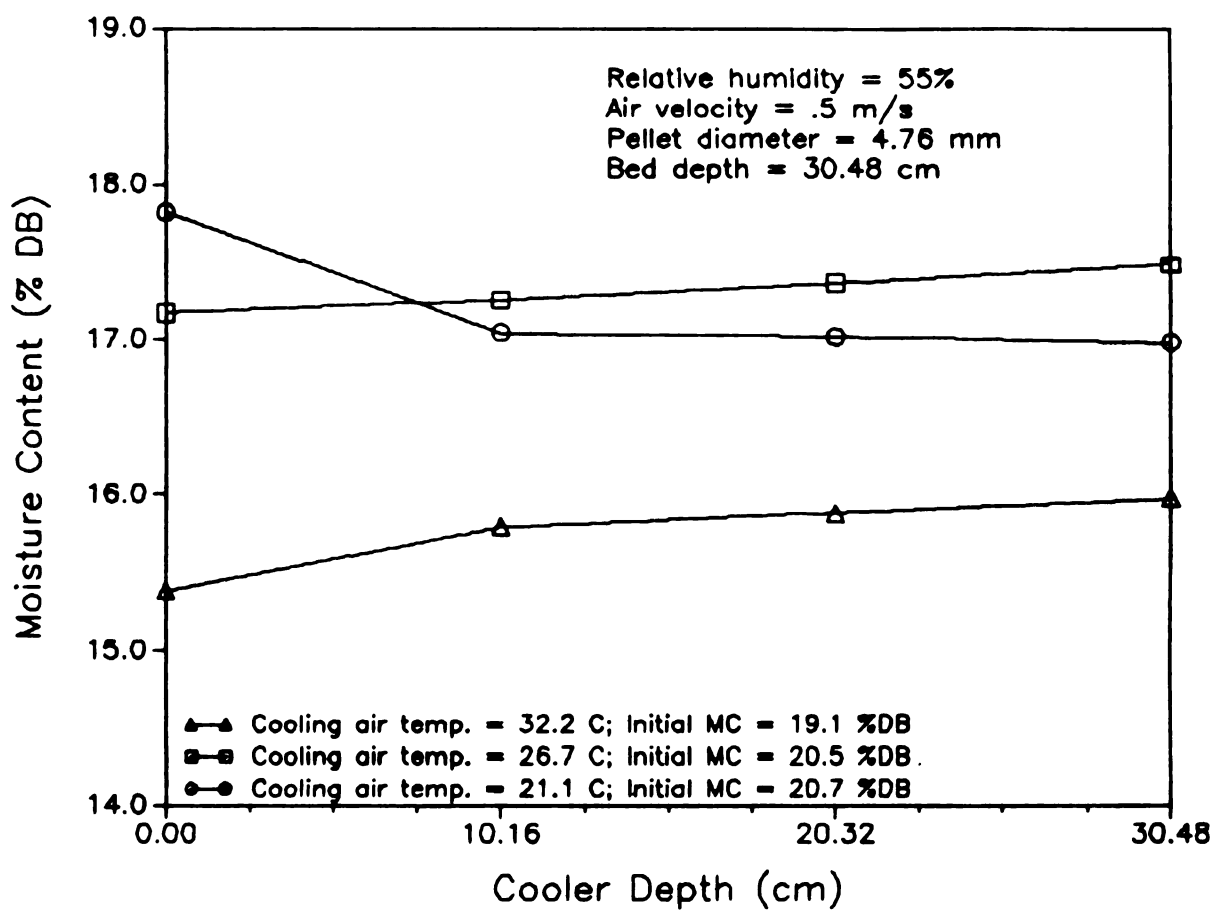


Fig. 6.7 Effect of cooling air temperature on the observed moisture content of a fixed bed of pellets after 20 min. of cooling.

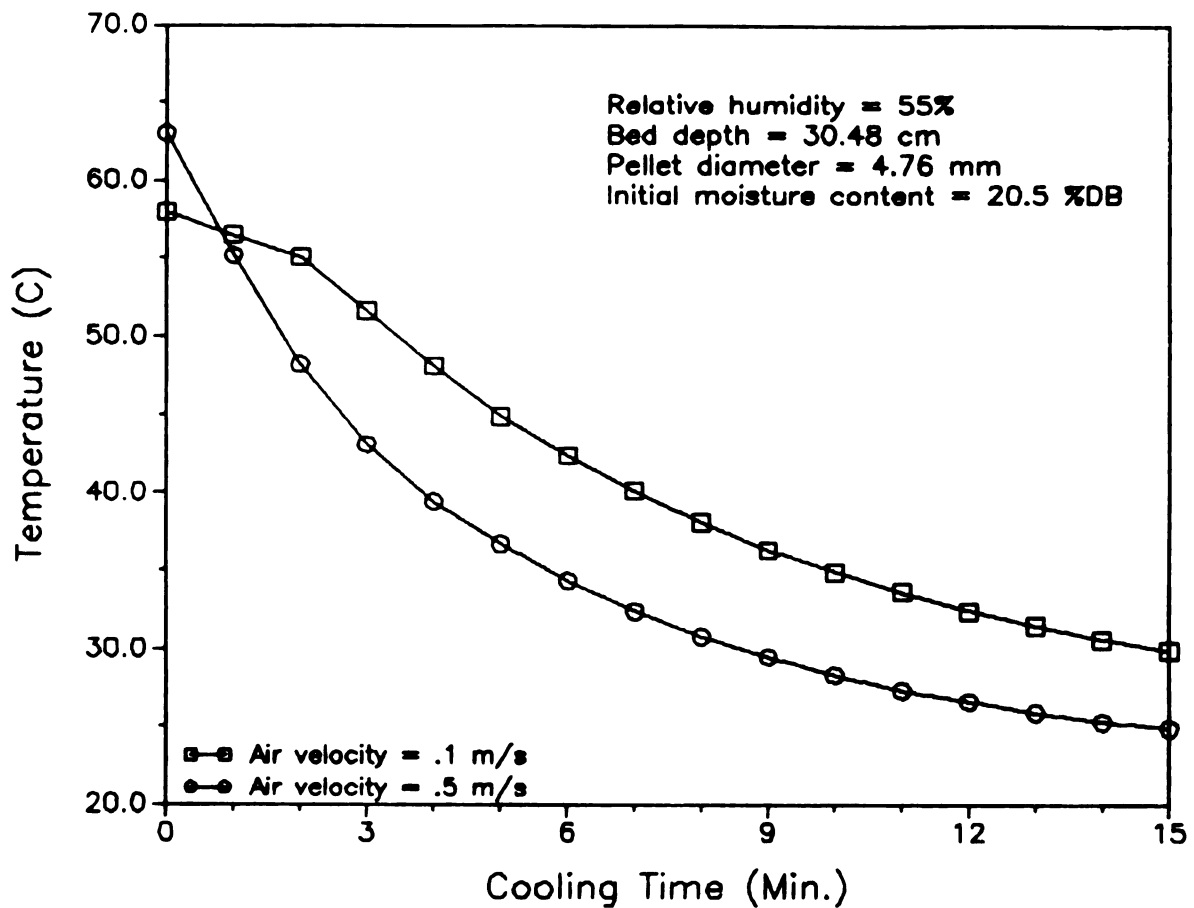


Fig. 6.8 Effect of air velocity on the observed temperatures at the top of a fixed bed of pellets.
Cooling air temperature 26.7 C.

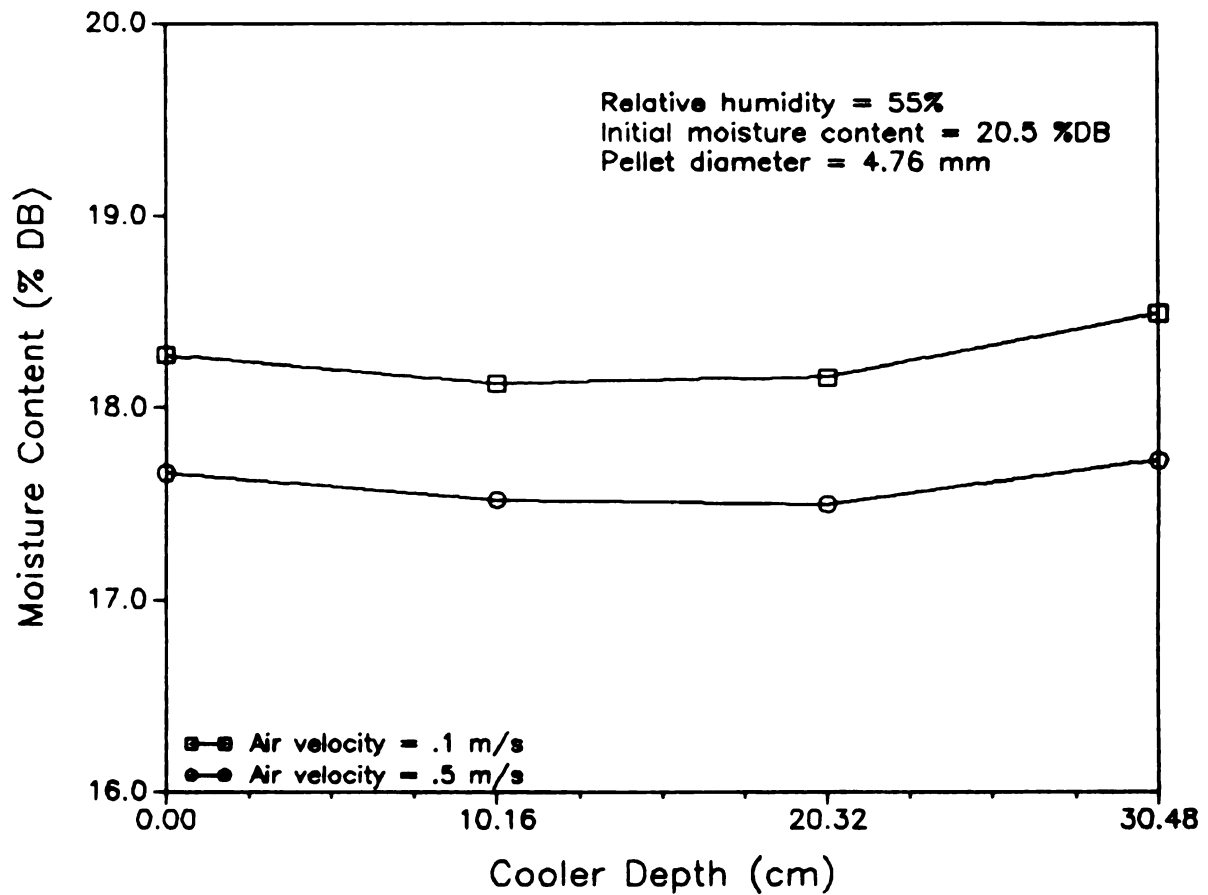


Fig. 6.9 Effect of air velocity on the observed moisture content of a fixed bed of pellets after 15 min. of cooling. Cooling air temp. 26.7 C.

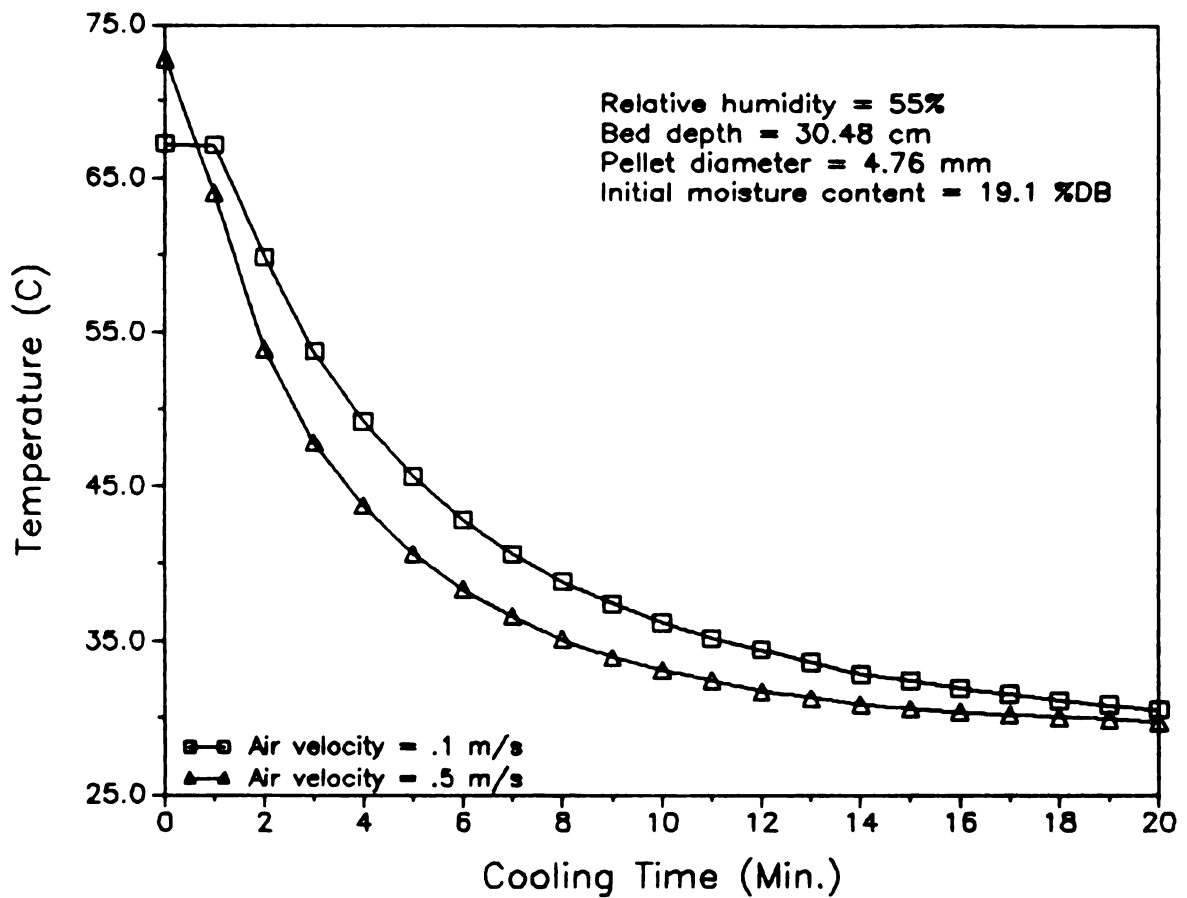


Fig. 6.10 Effect of air velocity on the observed temperatures at the top of a fixed bed of pellets.
Cooling air temperature 32.2 C.

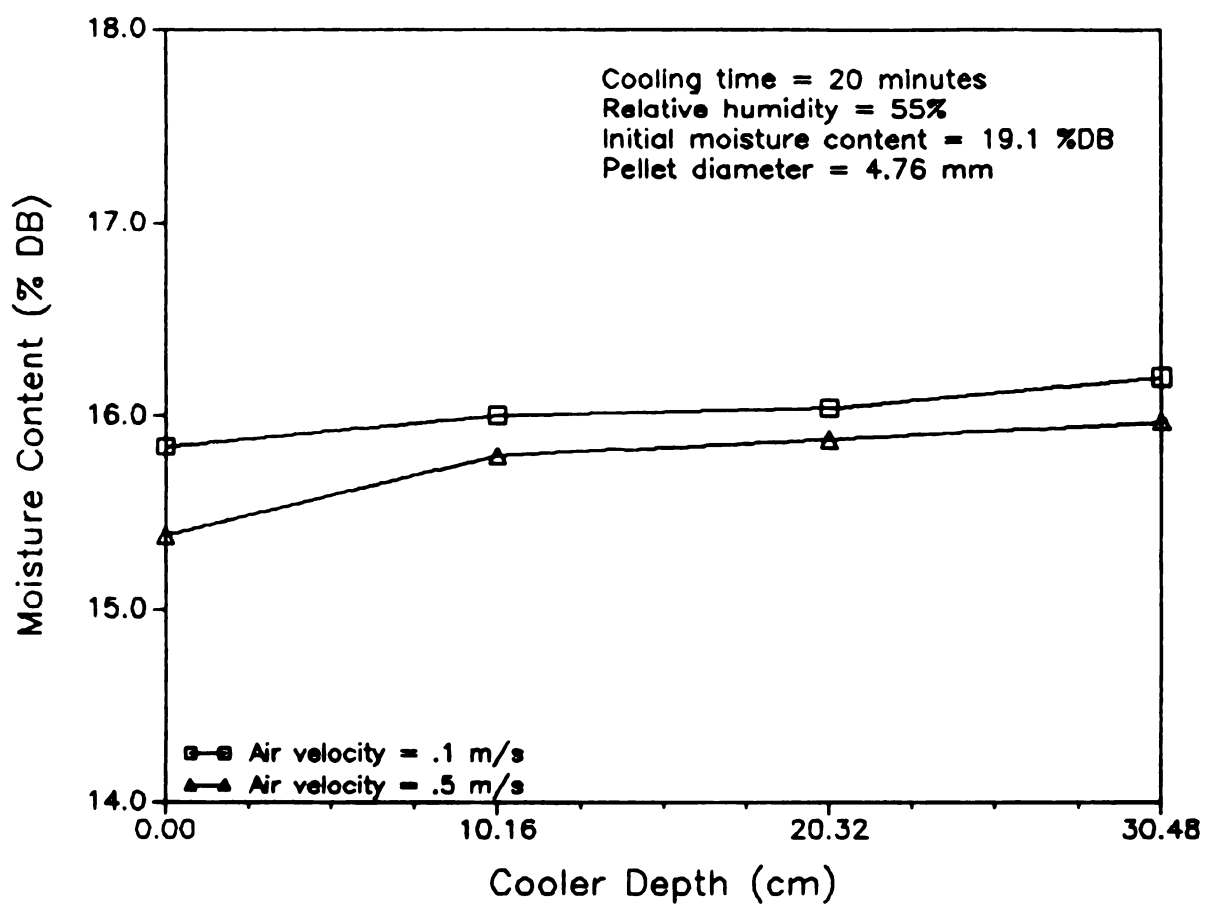


Fig. 6.11 Effect of air velocity on the observed moisture content of a fixed bed of pellets.
Cooling air temperature 32.2 C.

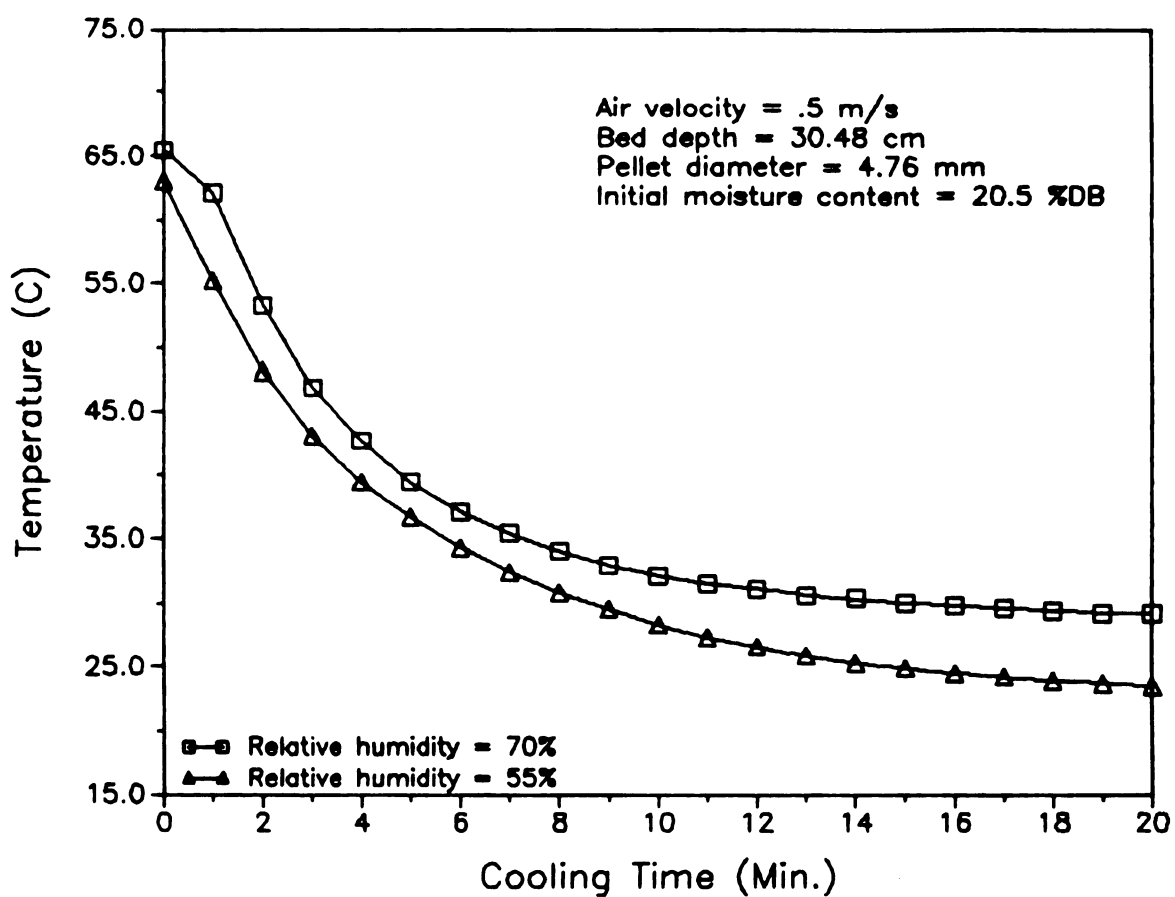


Fig. 6.12 Effect of relative humidity on the observed temperatures at the top of a fixed bed of pellets. Cooling air temperature 26.7 C.

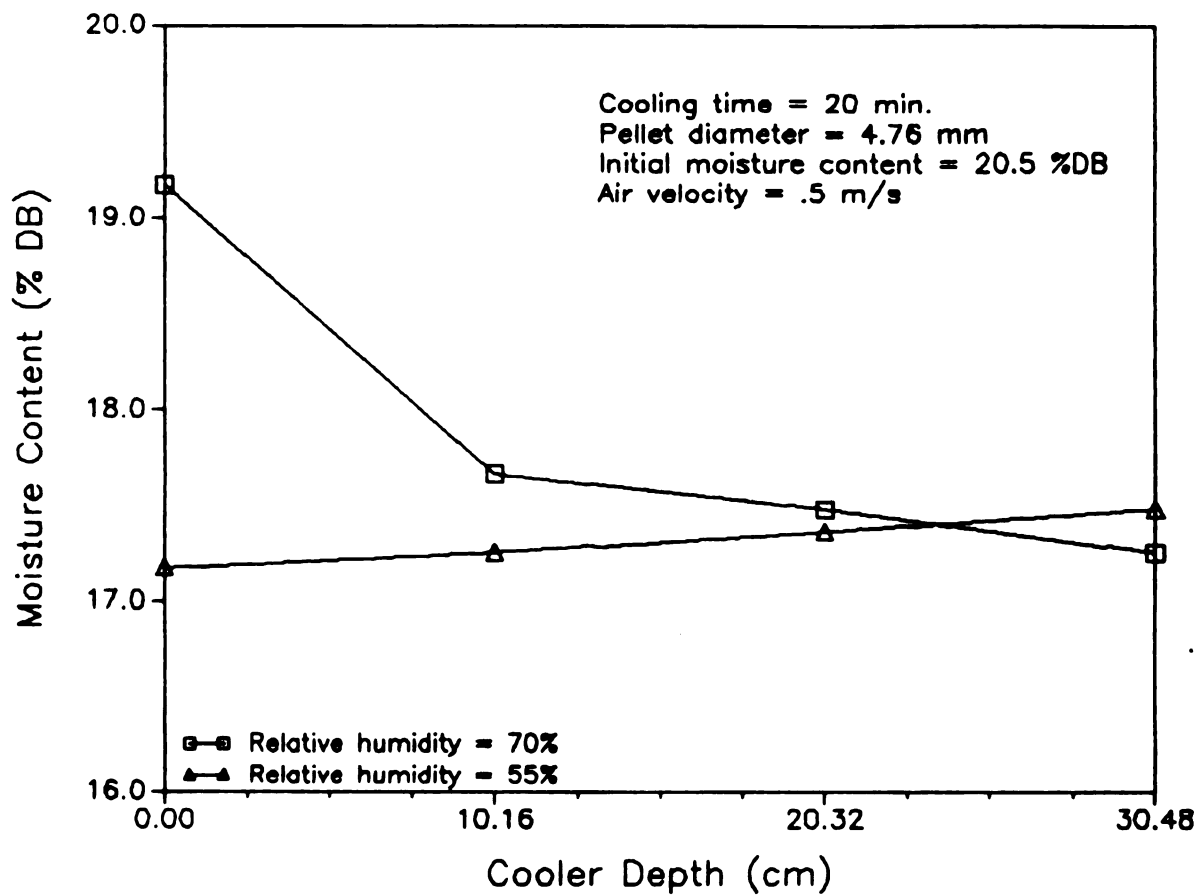


Fig. 6.13 Effect of relative humidity on the observed moisture content of a fixed bed of pellets. Cooling air temperature 26.7 C.

6.2.1 - Comparison of Experimental and Simulated Deep-Bed Data

The deep-bed pellet cooling heat and mass balance (HMB) and partial differential equations (PDE) models discussed in chapter 4 were used to simulate the cooling of pellets. The experimental conditions given in Table 5.2, and the model parameters shown in Table 6.8, formed the inputs to the simulation models of the fixed-bed cooler. The experimental and simulated results are compared in Figures 6.14 to 6.22.

Table 6.8 - Input Parameter Values to the Simulation Models of a Fixed-Bed Pellet Cooler.

Bed depth (cm)	30.48
Bed porosity	.44
Pellet bulk density (at MC=20.5 %DB) (Kg/m ³)	673
Heat transfer coefficient (W/M ² K)	Eqn. 3.25
Mass transfer coefficient (M/Hr)	Eqn. 3.26
Pellet specific heat (J/Kg K)	Eqn. 3.28
Pellet thermal conductivity (W/M K)	Eqn. 3.27
Equilibrium moisture content (dec. DB)	Eqn. 6.5
Diffusion coefficient (M ² /Hr)	Eqn. 6.6

The PDE model requires between three to five minutes execution time on the IBM-AT micro-computer to simulate one minute of cooling time. The HMB model requires only 10 to 15 seconds to simulate this period of cooling.

First, the equilibrium moisture content Equations (6.3), (6.4), and (6.5) were used in the PDE model to evaluate the effect of the EMC equation on the pellet moisture content. The results are shown in Figure 6.14

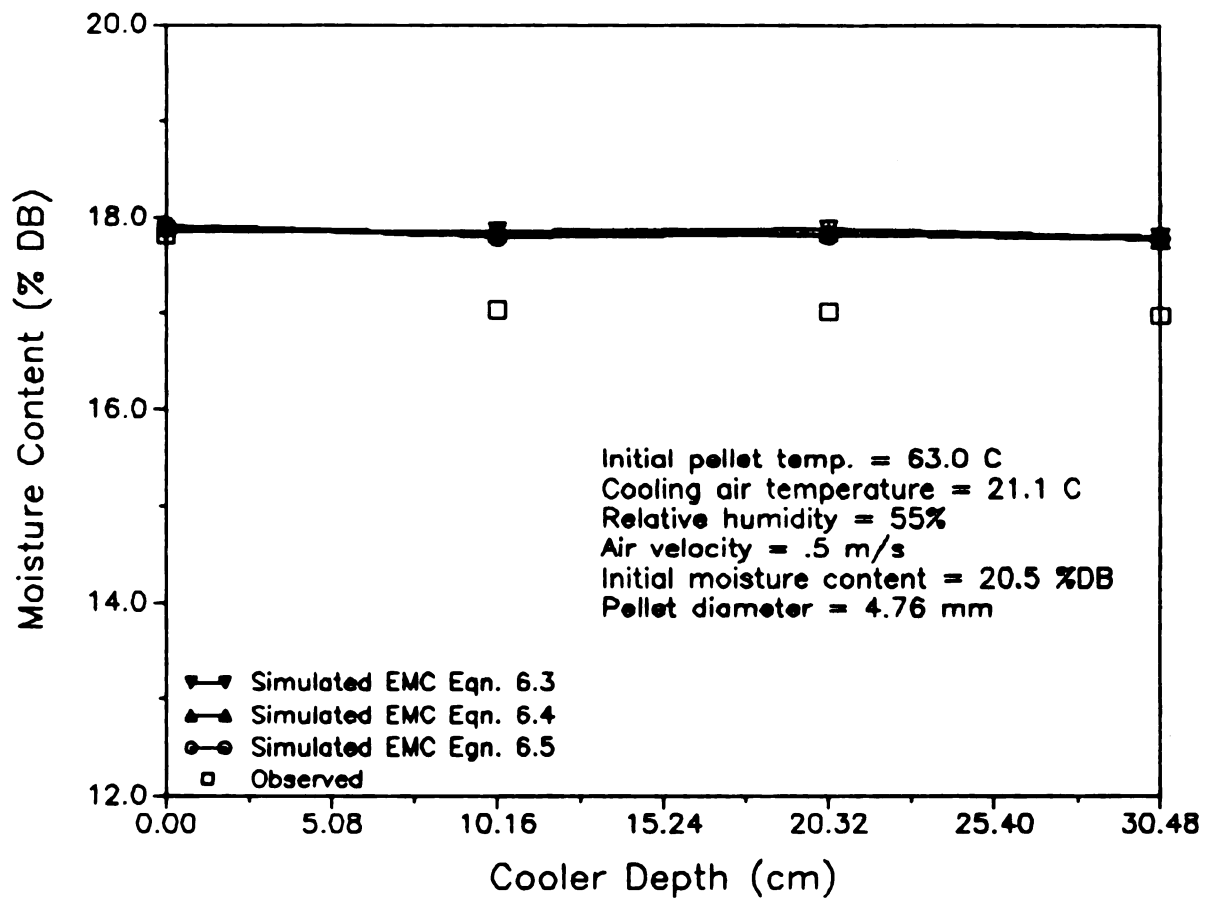


Fig. 6.14 Observed and simulated moisture content using three different EMC equations after 20 minutes of cooling.

together with the experimental values. The three equations predicted practically the same moisture content within the fixed-bed after 20 minutes of cooling. When compared with the observed data, the predicted results are in reasonably good agreement. The experimental and predicted values are about the same at the bottom of the cooler, and slightly different at the other bed locations. Although all three EMC equations predict the moisture content well, the Chung-Pfost equation (Eqn. 6.5) is used in all subsequent simulations conducted in this study, because it had the smallest mean relative deviation modulus (P) (see Table 6.2).

Figures 6.15 and 6.22 compare the experimental and the simulated values from the HMB and PDE models. Only the values at the bottom and top of the cooler are shown because these are the critical locations of the bed.

Both models predict the temperatures at the bottom very well at the airflow of .5 m/s (see Figure 6.15). At the top, the HMB model shows better agreement with the experimental data than the PDE model for the first 9 minutes of cooling but after that overpredicts the temperatures. The opposite happens with PDE model which overpredicts the temperatures in the first 10 minutes but is in a good agreement with the experimental data during the last 10 minutes of cooling.

The observed and simulated moisture contents are shown in Figure 6.16 for the cooling conditions of Figure 6.15. Both models give results fairly close to the experimental data, although the PDE model better predicts

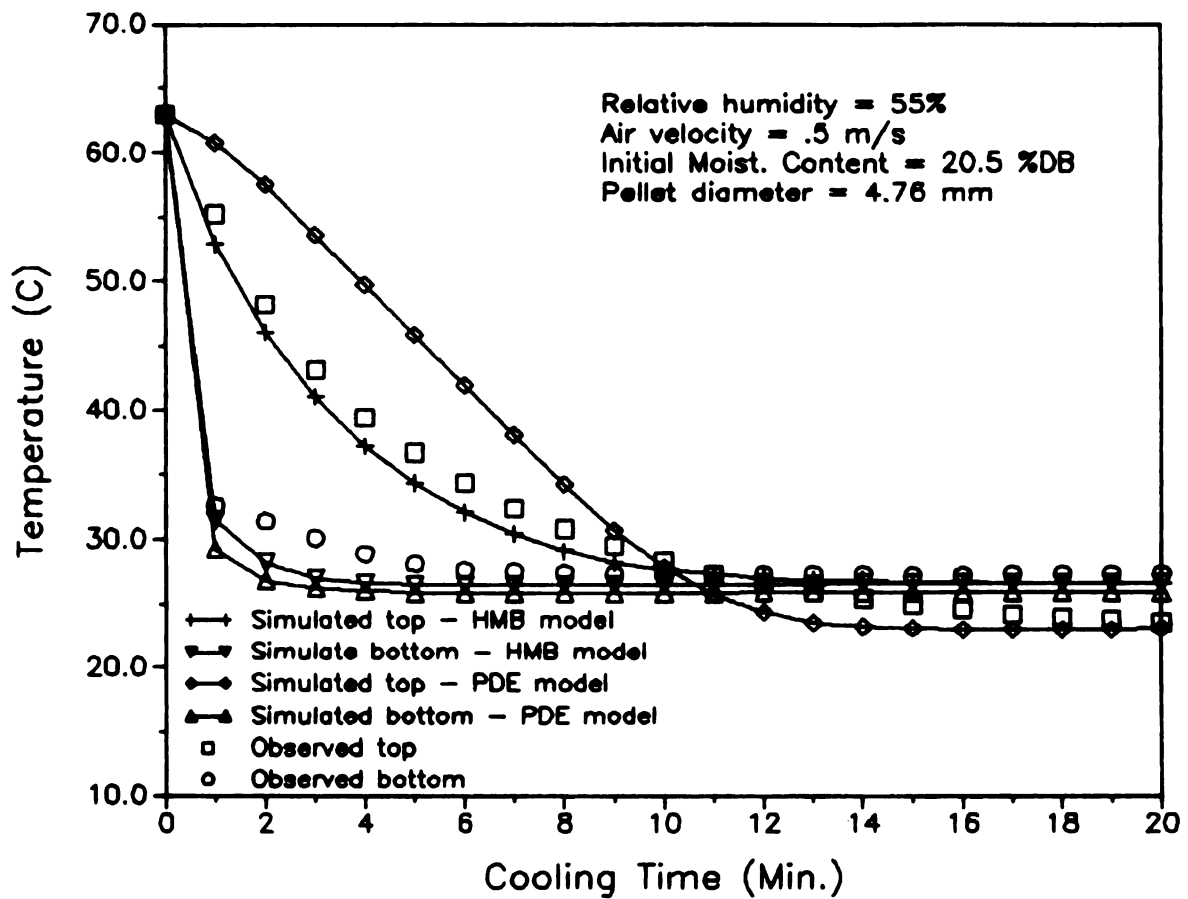


Fig. 6.15 Observed and simulated temperatures at the bottom and top layers of a fixed bed of pellets. Cooling air temperature = 26.7 C.

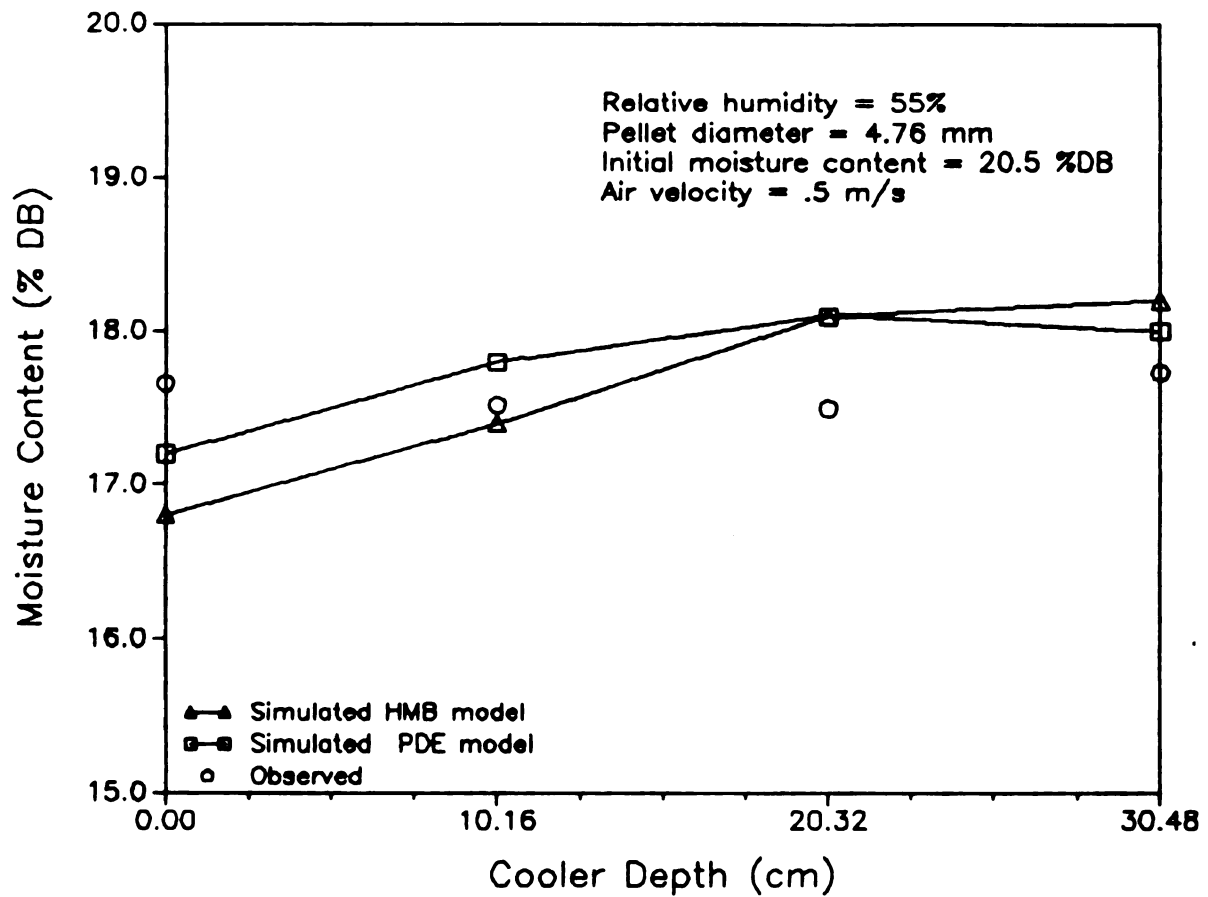


Fig. 6.16 Observed and simulated moisture content of a fixed bed of pellets after 20 min. of cooling. Cooling air temperature 26.7 C.

the pellet moisture content.

Figures 6.17 and 6.18 show the pellet temperature and moisture content, respectively, during the process of pellet cooling at .1 m/s. For the low air flow the HMB model better simulates the temperatures. The moisture content, (see Figure 6.18) is predicted well by the PDE model at the bottom of the bed, but is underpredicted by the PDE model and overpredicted by the HMB model at the other bed locations. Still, the difference between observed and simulated moisture content is within 10%.

Figures 6.19 and 6.20 show the pellet temperature and moisture, respectively, for cooling test 11 in Table 5.2. The trends are the same as in Figures 6.15 and 6.16, except that both models slightly underpredict the temperatures during the last 10 minutes of cooling time. The moisture content values are better simulated by the PDE model. The final moisture content of the pellets was high at the bottom of the cooler for this test because of the high relative humidity (70%). Thus, the bottom-layer pellets equilibrated to a relatively high moisture content. Since the pellet temperature at the top of the cooler is higher for higher relative humidities, the pellets tend to equilibrate at a lower moisture content.

Figures 6.21 and 6.22 represent the experimental and simulated values of temperature and moisture content for test 7. The profile of the temperature curves are similar as in Figure 6.15; the moisture content at the bottom is higher than the moisture content at the top of the cooler.

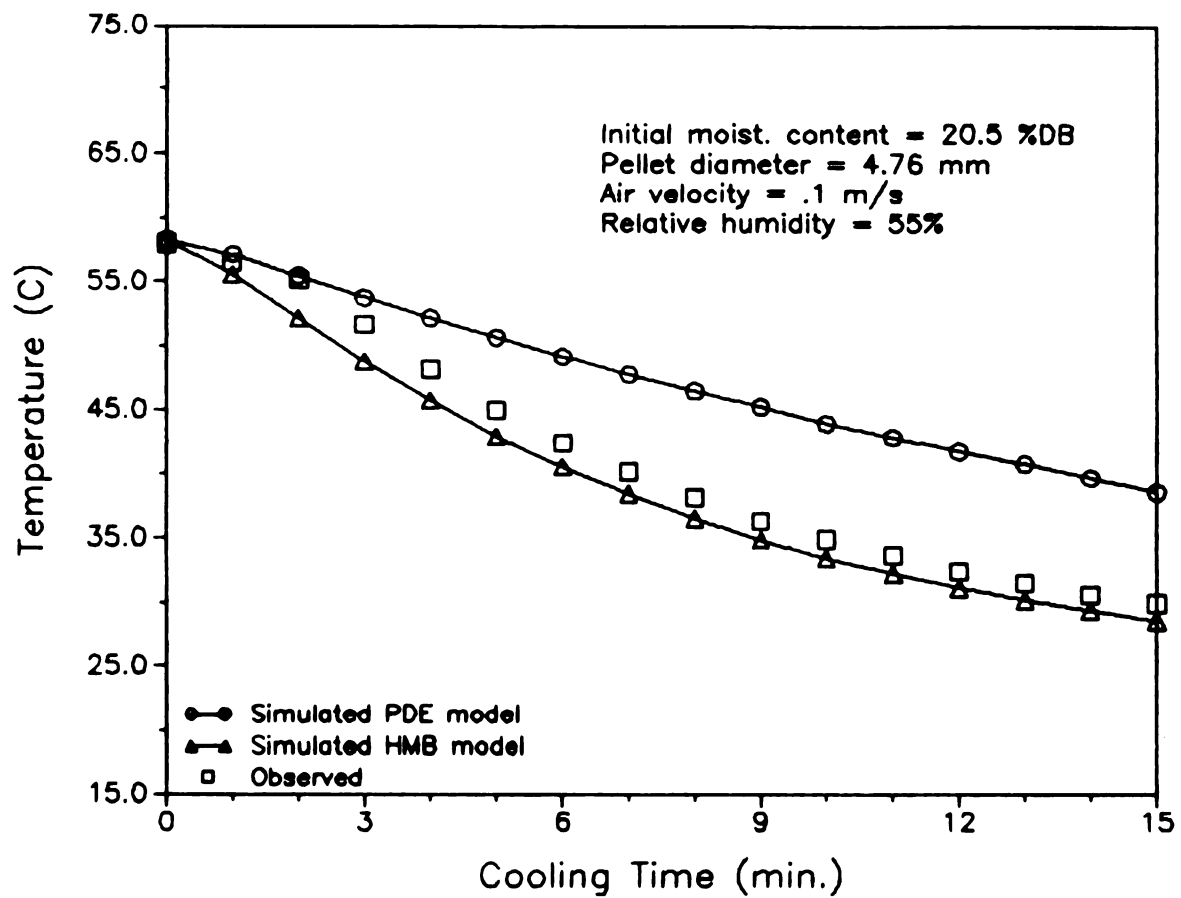


Fig. 6.17 The observed and simulated temperatures at the top of a fixed bed of pellets. Cooling air temperature 26.7 C..

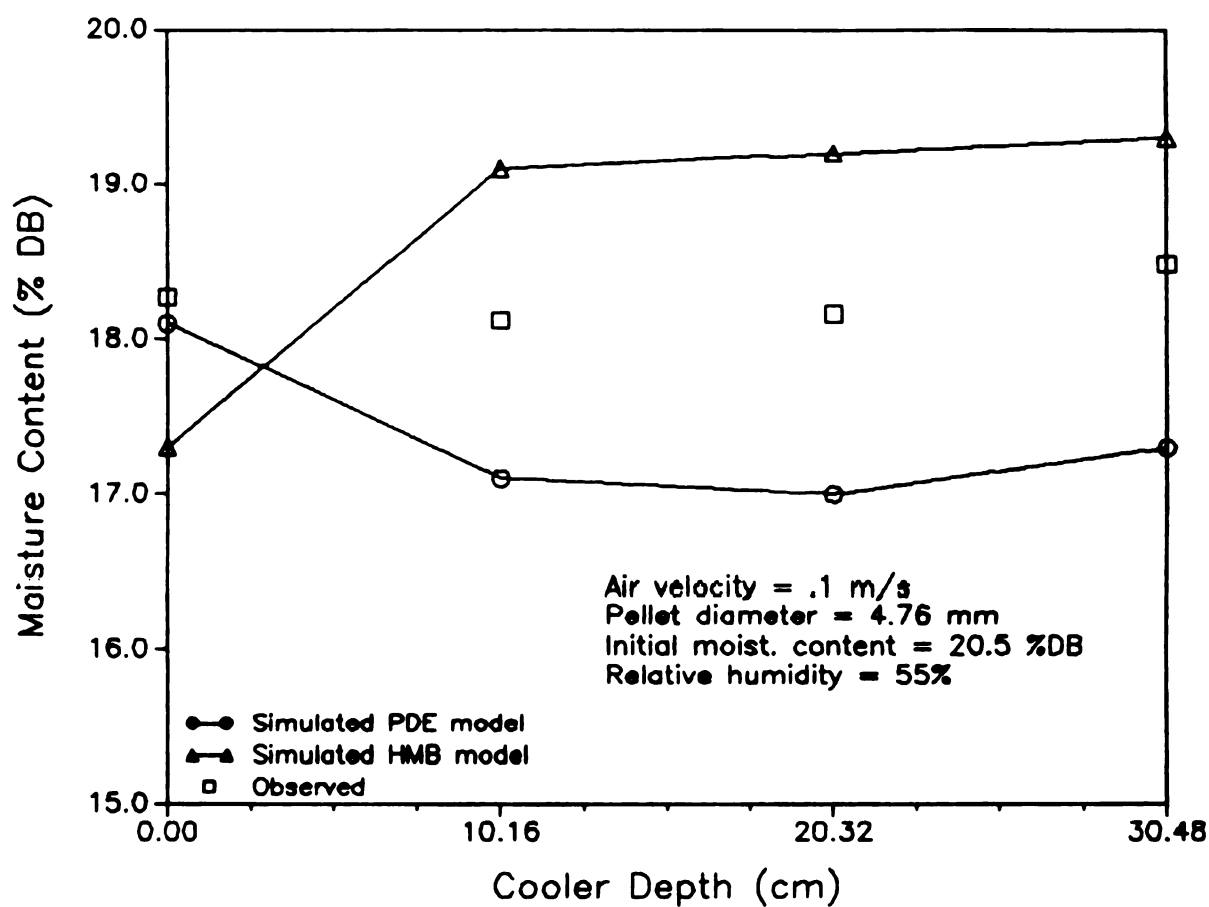


Fig. 6.18 Observed and simulated moisture content of a fixed bed of pellets after 15 min. of cooling. Cooling air temperature 26.7 C.

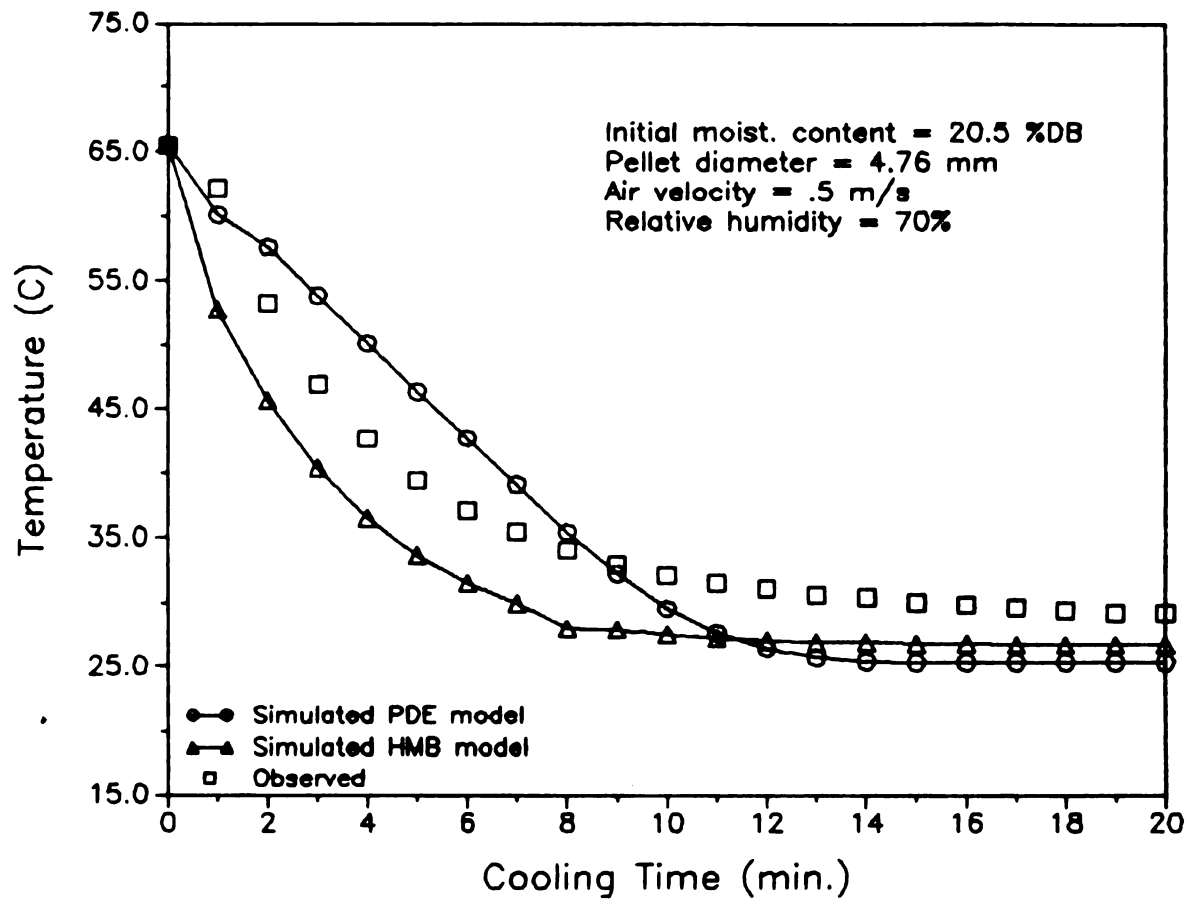


Fig. 6.19 Observed and simulated temperatures at the top layer of a fixed bed of pellets.
Cooling air temperature = 26.7 C.

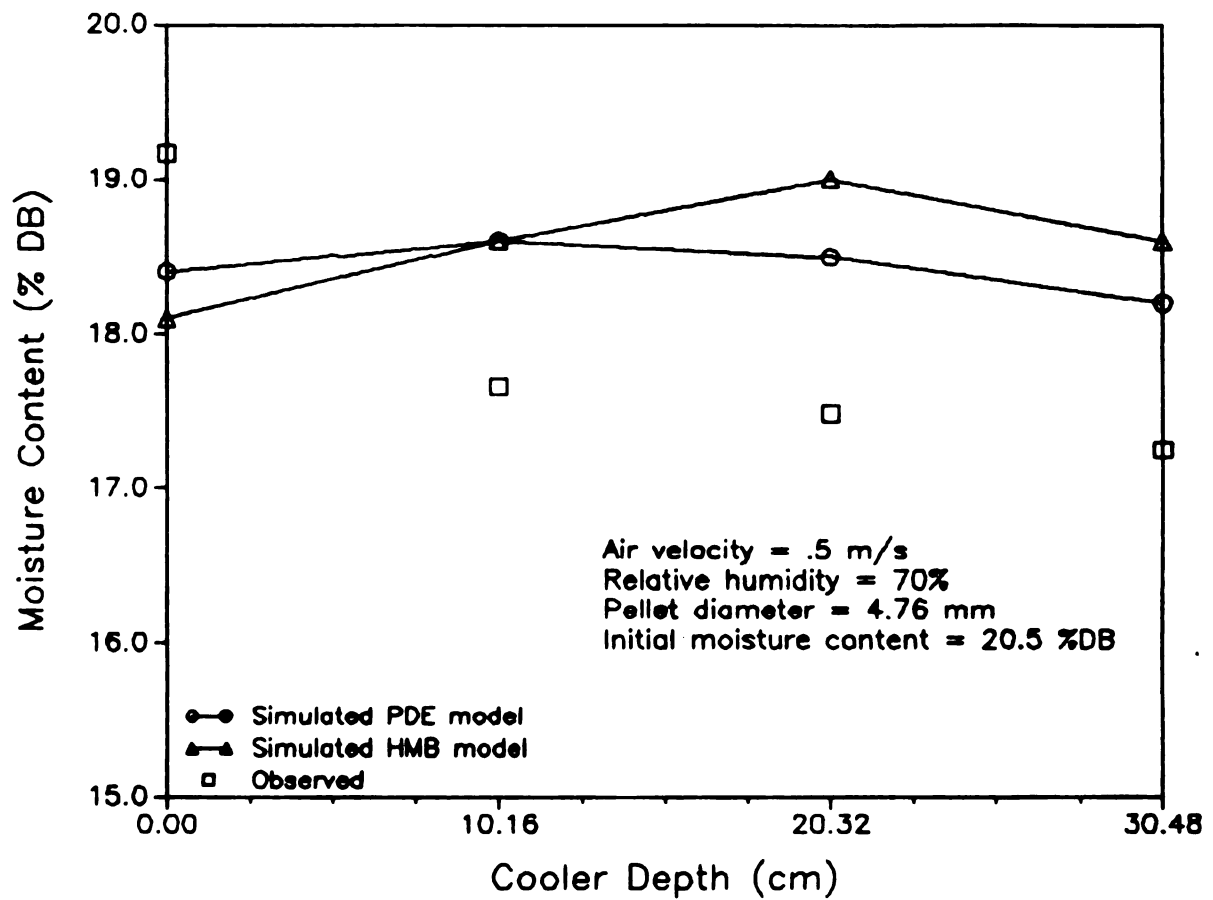


Fig. 6.20 Observed and simulated moisture content of a fixed bed of pellets after 20 min. of cooling. Cooling air temperature 26.7 C.

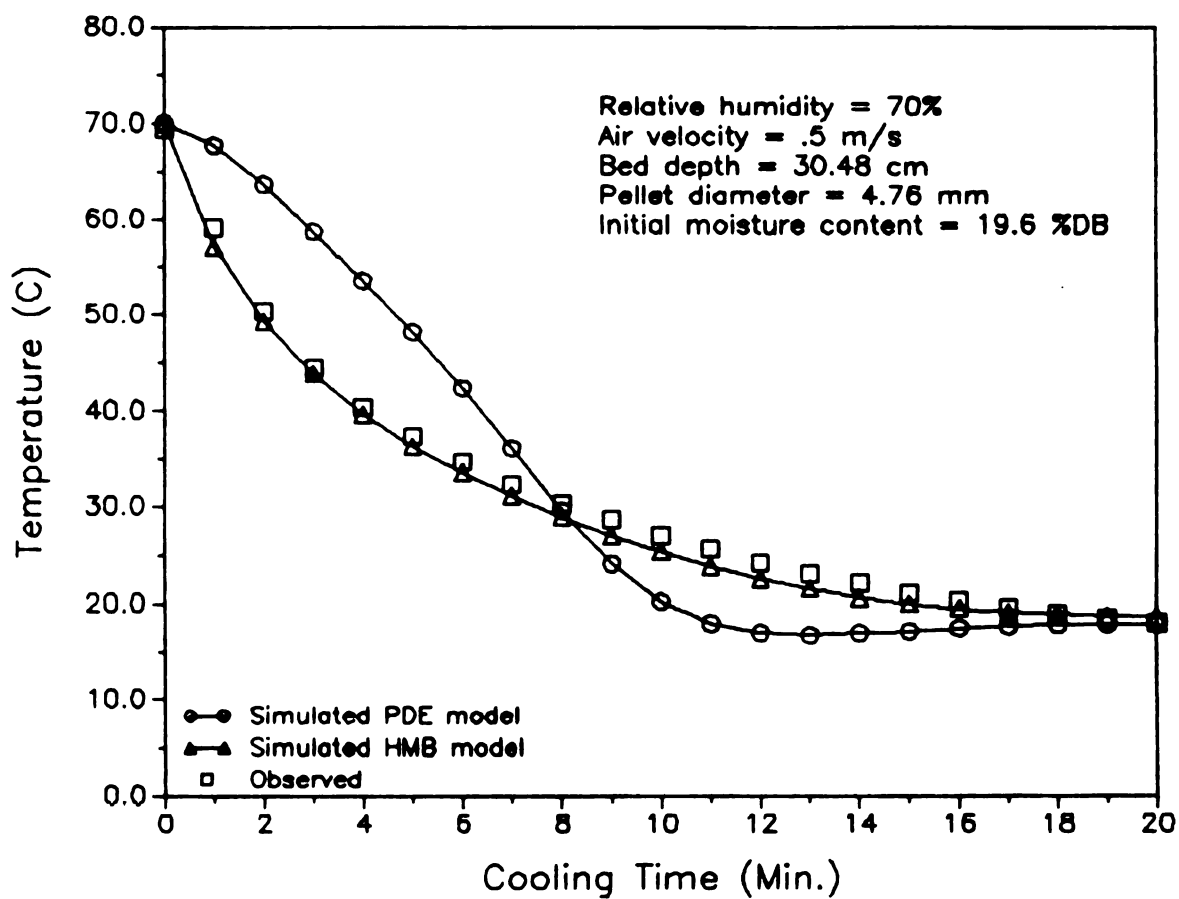


Fig. 6.21 Observed and simulated temperatures at the top layer of a fixed bed of pellets.
 Cooling air temperature = 17.7 C.

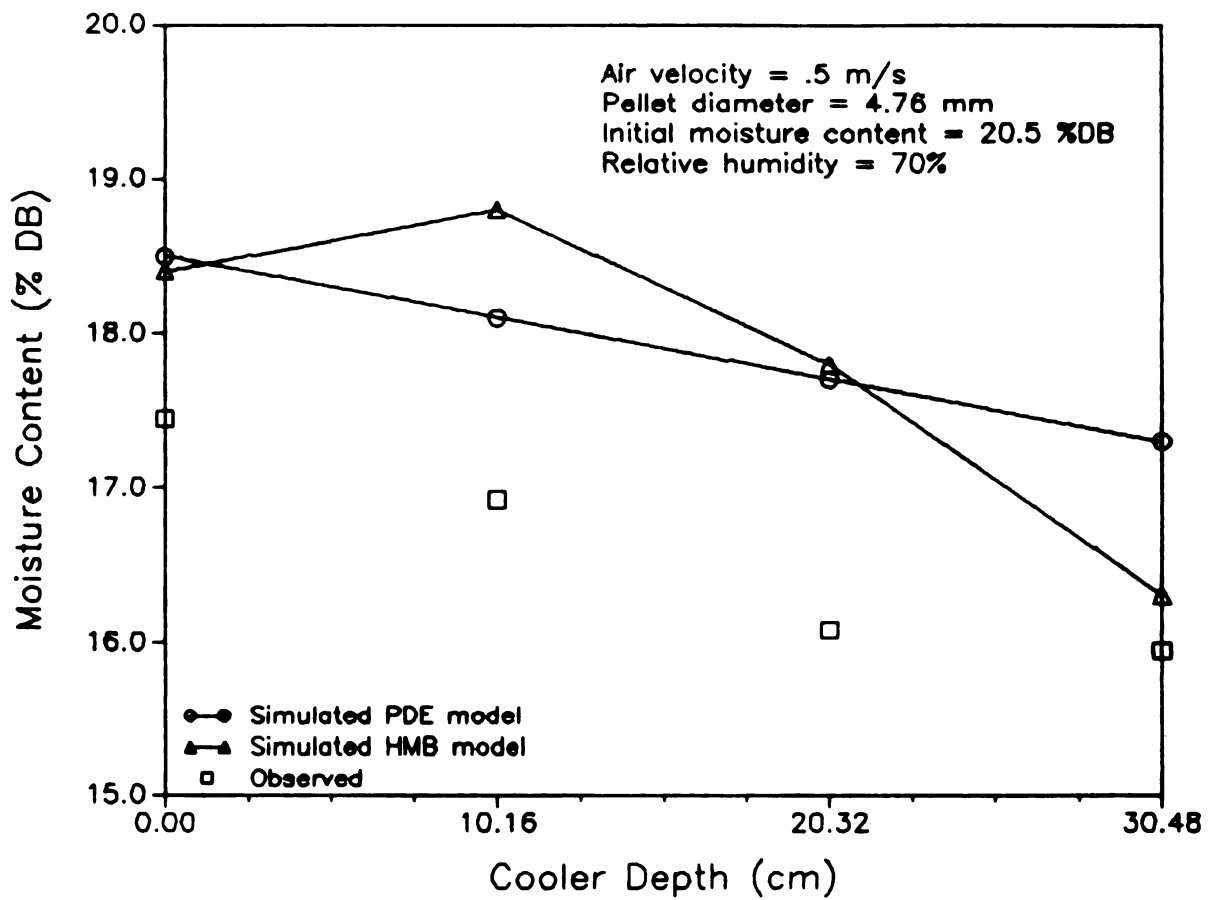


Fig. 6.22 Observed and simulated moisture content of a fixed bed of pellets after 20 min. of cooling. Cooling air temperature 17.7 C.

Based on Figures 6.15 - 6.22, it is concluded that the agreement between the experimental data and the values simulated by the HMB and PDE models is acceptable.

The HMB model better predicts the pellet temperature at low air flow rates and during the first 10 minutes of cooling, but does not simulate the moisture content as good as the PDE model.

The computer time plays an important role when selecting a simulation model. The HMB model can be used for a quick simulation of deep-bed pellet cooling and for an evaluation of the influence of selected parameters on the cooling process such as the cooling air temperature and humidity, the pellet temperature and moisture content, and the air flow rate.

Although the PDE model requires longer computer time, it is more fundamental in nature (i.e. it contains fewer simplifications) and the results appear to be more accurate. Therefore, it will be used in the next section to evaluate the effect of the pellet thermal conductivity, specific heat, density, heat and mass transfer coefficients on the pellet cooling process.

6.3 - Effect of Model Parameter Values

In this section the effect of several model parameters (shown in Table 6.9) on the pellet temperature and moisture content will be analysed.

Table 6.9 - Standard Input Parameter Values Used in the PDE Model of a Fixed-Bed Pellet Cooler.

Cooling air temperature (C)	26.7
Relative humidity (%)	55.0
Air velocity (m/s)	.5
Initial pellet temperature (C)	63.5
Initial pellet moisture content (% DB)	20.5
Pellet diameter (mm)	4.76
Bed depth (cm)	30.48
Pellet bulk density (at MC=20.5 %DB) (kg/m ³)	673
Heat transfer coefficient (W/m ² K)	Eqn. 3.25
Mass transfer coefficient (M/h)	Eqn. 3.26
Pellet specific heat (J/kg K)	Eqn. 3.28
Pellet thermal conductivity (W/m K)	Eqn. 3.27
Equilibrium moisture content (% DB)	Eqn. 6.5
Diffusion coefficient (m ² /h)	Eqn. 6.6
Bed porosity (decimal)	.44

The effects of the values of the parameters in Table 6.9 on the temperatures and moisture contents in a deep-bed of pellets is illustrated in Figures 6.23 - 6.34.

Figures 6.23 and 6.24 show the effect of pellet density on temperature and moisture content. Two pellet bulk density values are compared: 673 and 801 Kg/m³, assuming that D is not a function of pellet density. The pellet temperature is higher for the higher pellet density while the pellet moisture content is lower.

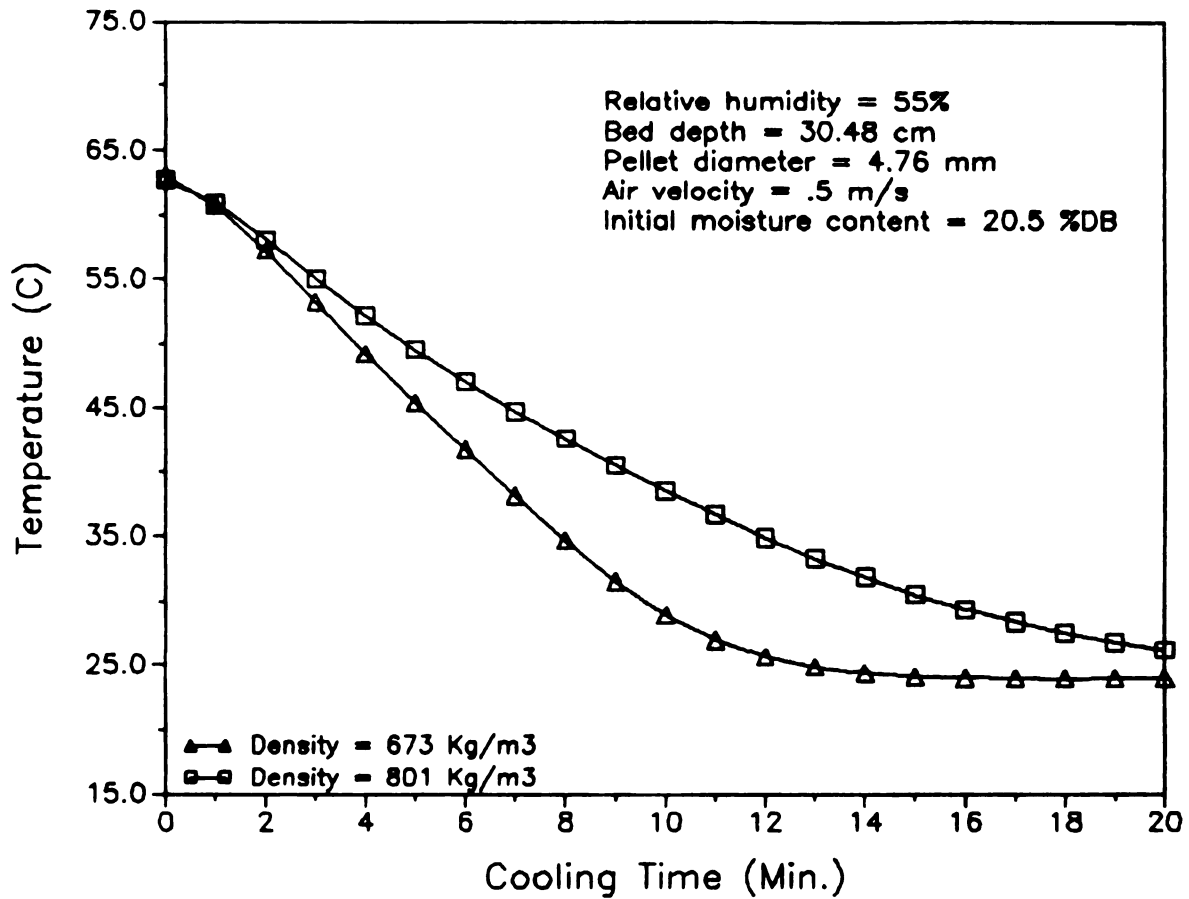


Fig.6.23 Effect of pellet density on the simulated temperatures at the top of fixed bed of pellets.
Cooling air temperature = 26.7 C.

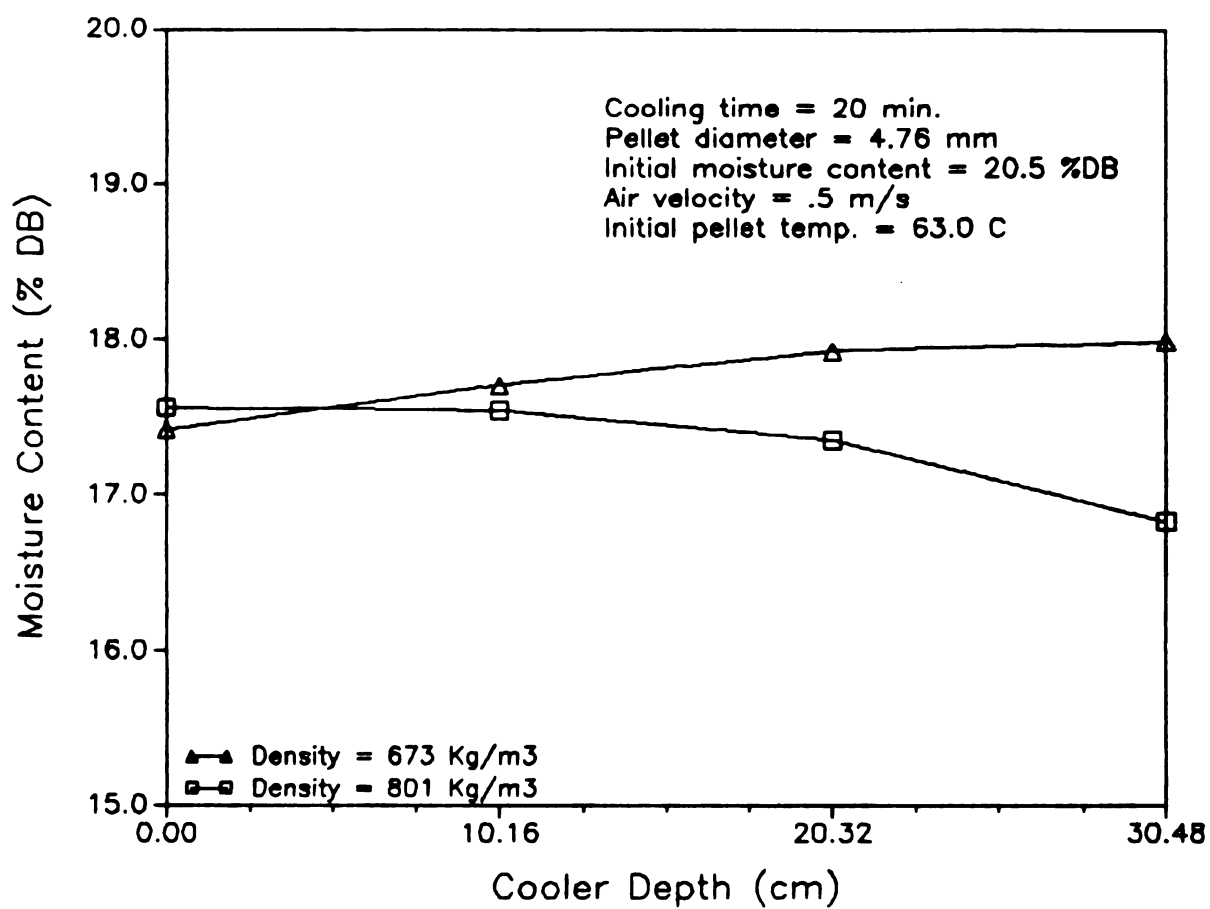


Fig. 6.24 Effect of pellet density on the simulated moisture content of a fixed bed of pellets. Cooling air temperature 26.7 C.

Three values for the heat transfer coefficient 80, 106, and 120 W/m² K, are compared. The value of 106 W/m² K was calculated by Equation (3.25) under the conditions of Table 6.9. Figure 6.25 shows that the heat transfer coefficient has a marked influence on the rate at which the pellet temperature approaches equilibrium. For $h = 80$ W/m² K, the pellet temperature is 40 C after 10 minutes cooling while for $h = 120$ W/m² K it is about 20 C at the top of the cooler. The heat transfer coefficient not only affects the pellet temperature but also affects the predicted moisture content (see Figure 6.26), because the moisture diffusivity is a function of the pellet temperature. For $h = 80$ W/m² K, the computed moisture content at the top of the cooler is 16.5 %DB, while for $h = 120$ W/m² K this value is 18.4 %DB.

Figures 6.27 and 6.28 show the influence of the mass transfer coefficient on the pellet temperature and moisture, respectively. The .0126 M/Hr value is computed by Equation (3.26) for the conditions given in Table 6.8. For the three values of the mass transfer coefficient (.009, .0126, and .025 m/h) used, the difference in the pellet temperature is not large. A lower value in the mass transfer coefficient results in a slightly higher pellet moisture content at the air inlet side of the cooler (see Figure 6.28).

Figures 6.29 and 6.30 illustrate the effect of the specific heat on the pellet temperature and moisture content. Two fixed values of the specific heat 1700 and 2100 J/Kg K, and a specific heat value varying with the pellet

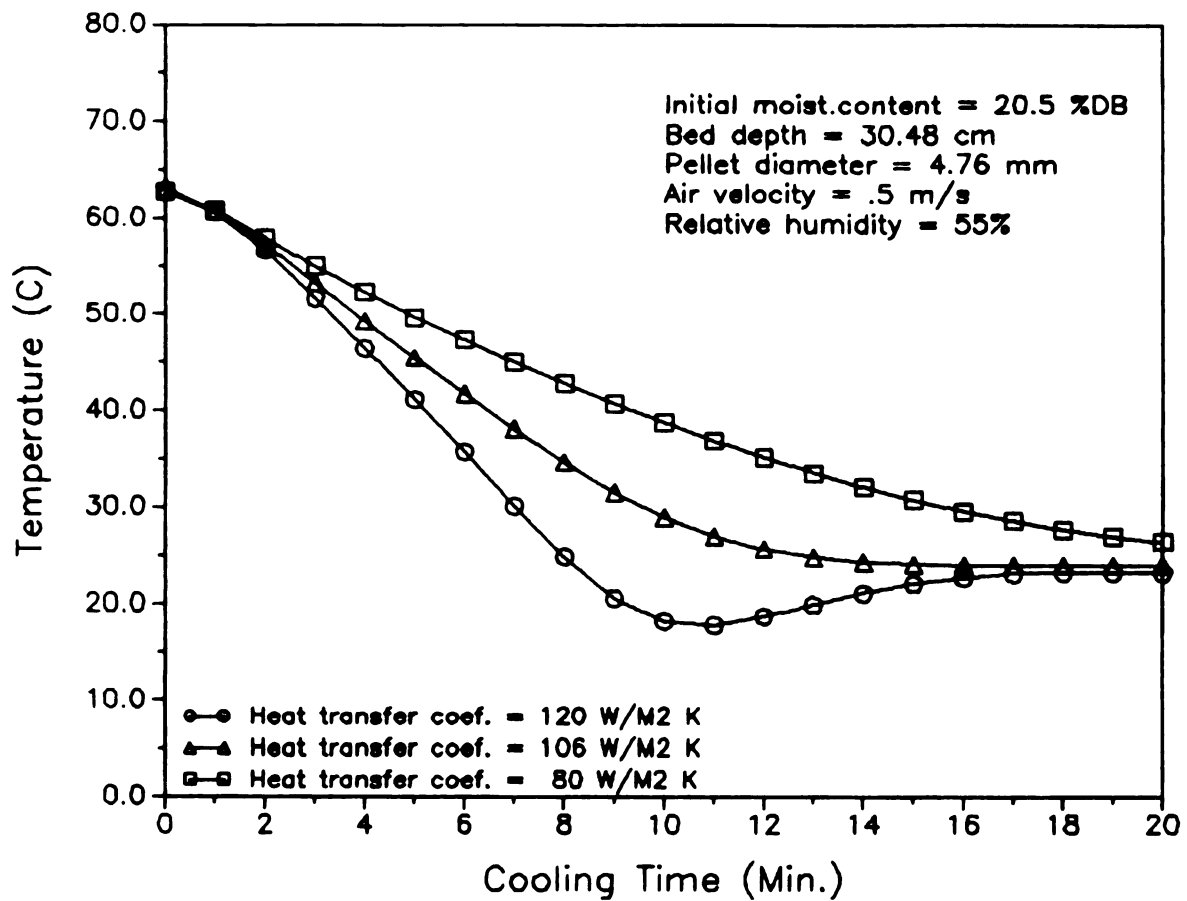


Fig. 6.25 Effect of heat transfer coefficient on the simulated temperatures at the top of a fixed bed of pellets. Cooling air temperature 26.7 C.

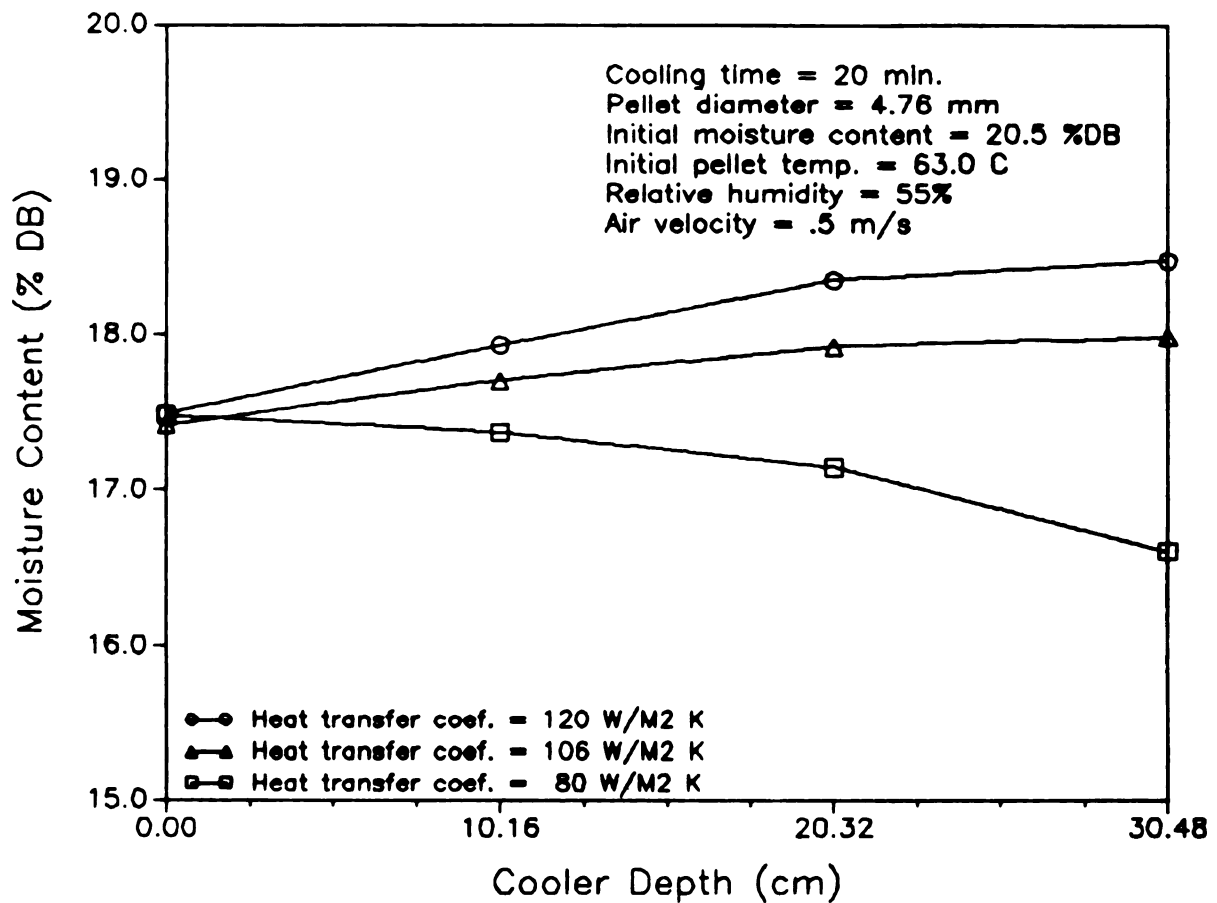


Fig. 6.26 Effect of heat transfer coefficient on the simulated moisture content of a fixed bed of pellets. Cooling air temperature 26.7 C.

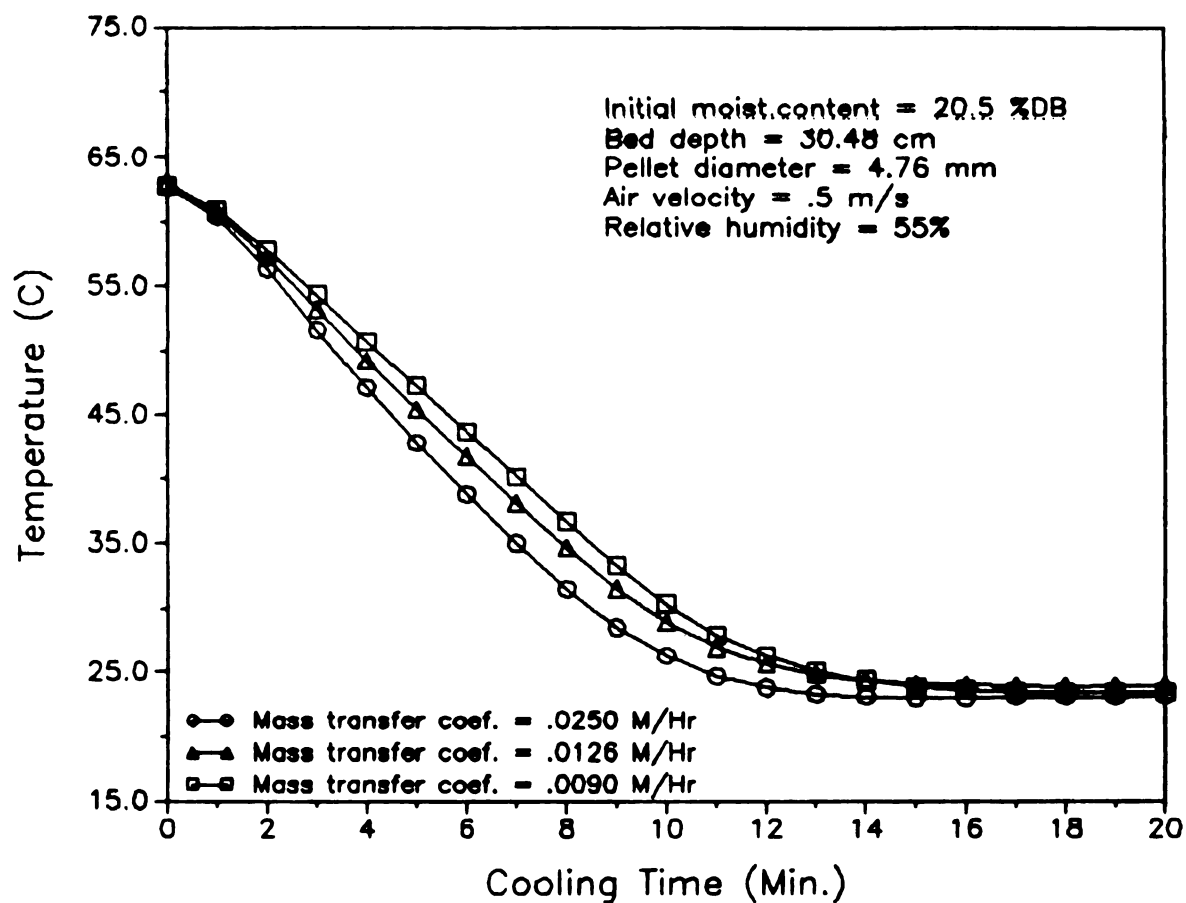


Fig. 6.27 Effect of mass transfer coefficient on the simulated temperatures at the top of a fixed bed of pellets. Cooling air temperature 26.7 C.

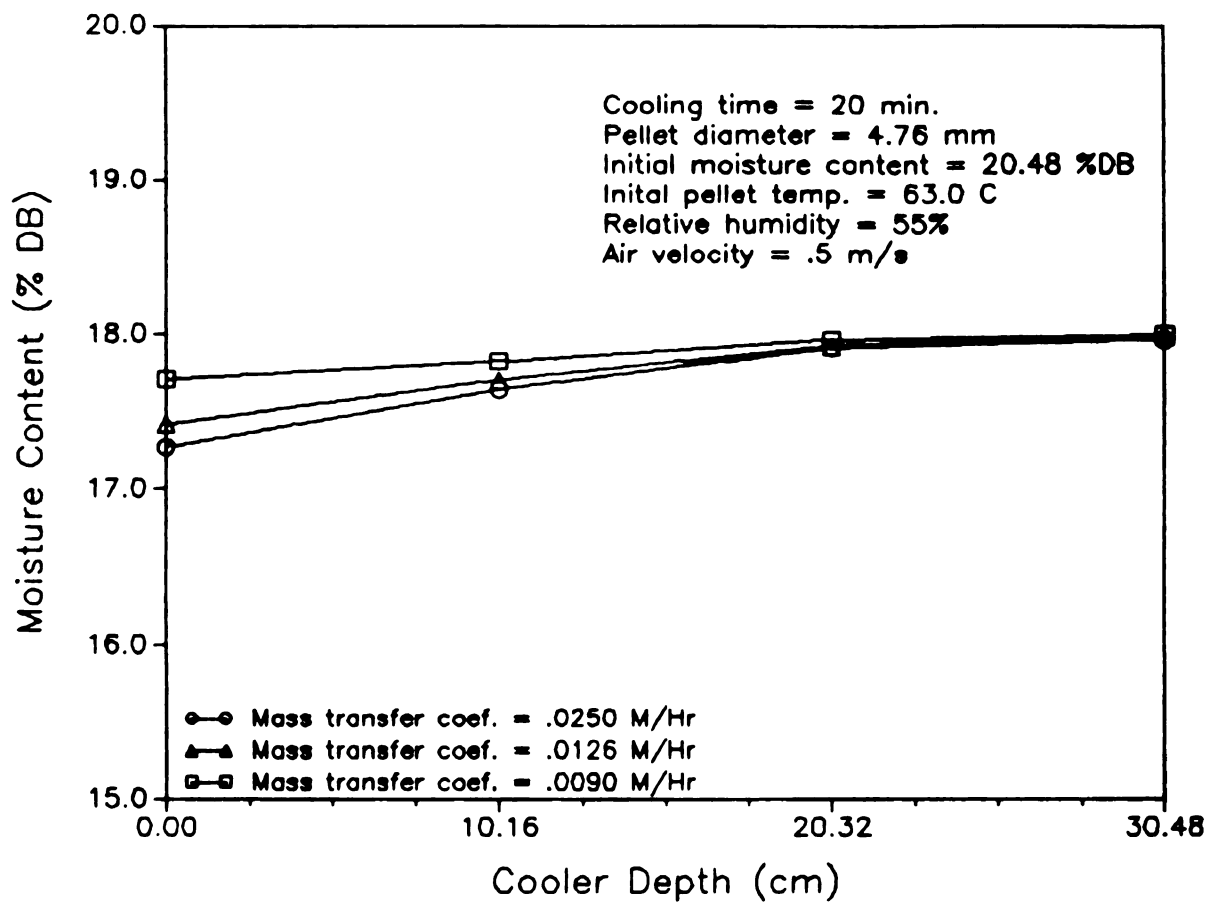


Fig. 6.28 Effect of mass transfer coefficient on the simulated moisture content of a fixed bed of pellets. Cooling air temperature 26.7 C.

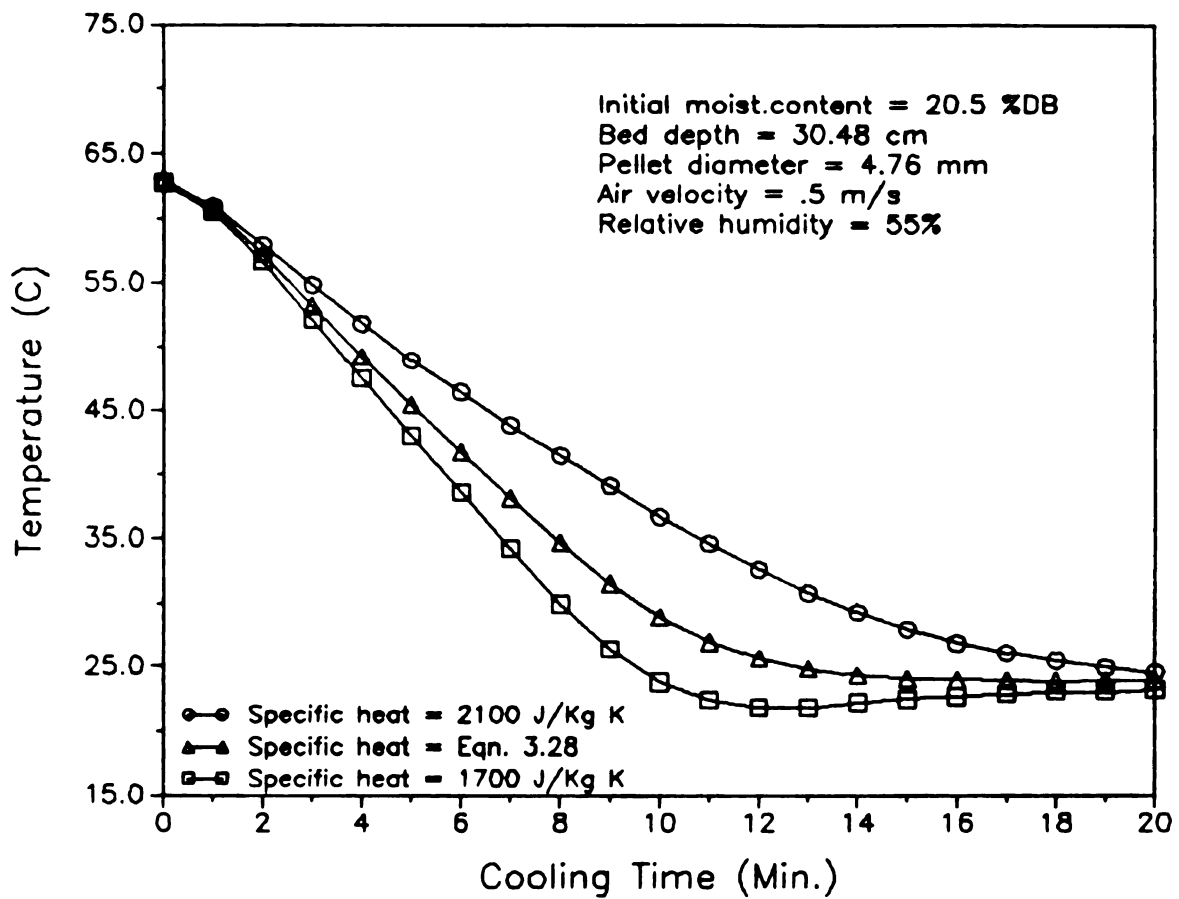


Fig. 6.29 Effect of specific heat on the simulated temperatures at the top of a fixed bed of pellets. Cooling air temperature 26.7 C.

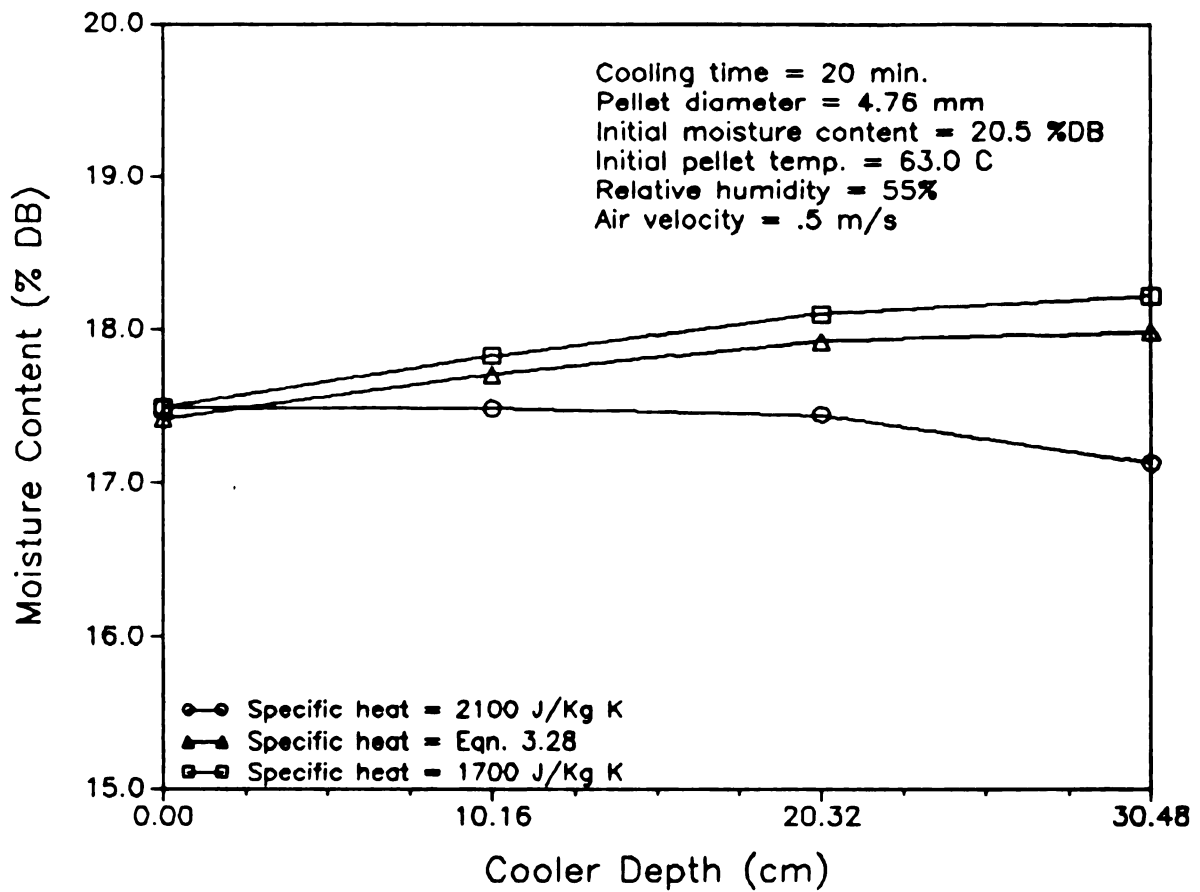


Fig. 6.30 Effect of specific heat on the simulated moisture content of a fixed bed of pellets.
 Cooling air temperature 26.7 C.

moisture content (Equation 3.28), are compared. A small value of the specific heat results in lower pellet temperature and high moisture content.

The effect of the thermal conductivity on the pellet temperature and moisture content is shown in Figures 6.31 and 6.32. Two fixed values (.10 and .17 W/m K), and a thermal conductivity value varying with the pellet moisture content (Equation 3.27), were used. The changes in the thermal conductivity neither affects the pellet temperature nor the moisture content significantly.

Figures 6.33 and 6.34 show the effects of the bed porosity (.35, .44, and .50) on the pellet temperature and moisture content. In this range of bed porosities, the values of pellet temperature are practically the same; for the moisture content, a lower value of bed porosity results in a slightly lower moisture content.

From the analysis in this section it is evident that the parameters that most affect the pellet temperature and moisture content are the pellet density, the heat and mass transfer coefficients, and the specific heat. The exact values of these parameters are not known; the values used in the PDE model are educated guesses. This illustrates the need for fundamental data for pelleted feeds.

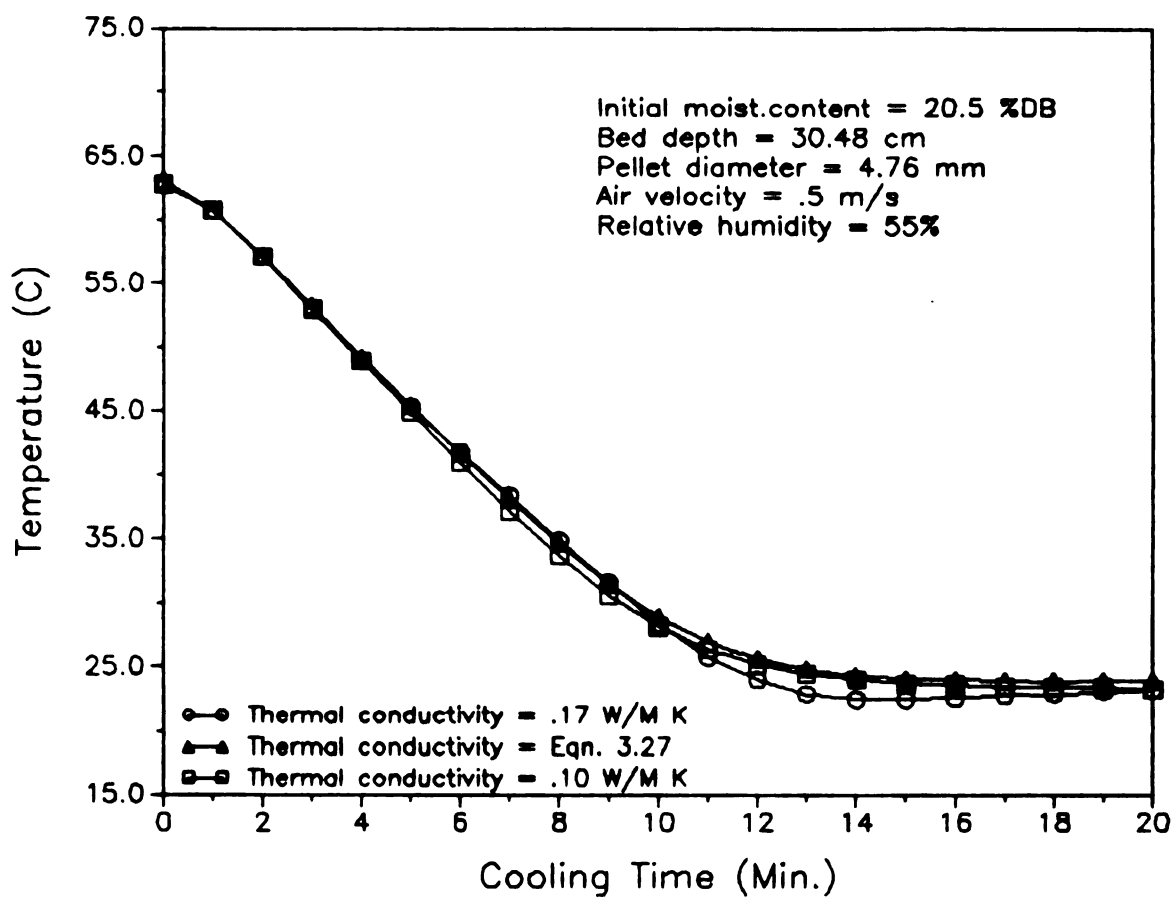


Fig. 6.31 Effect of thermal conductivity on the simulated temperatures at the top of a fixed bed of pellets. Cooling air temperature 26.7 C.

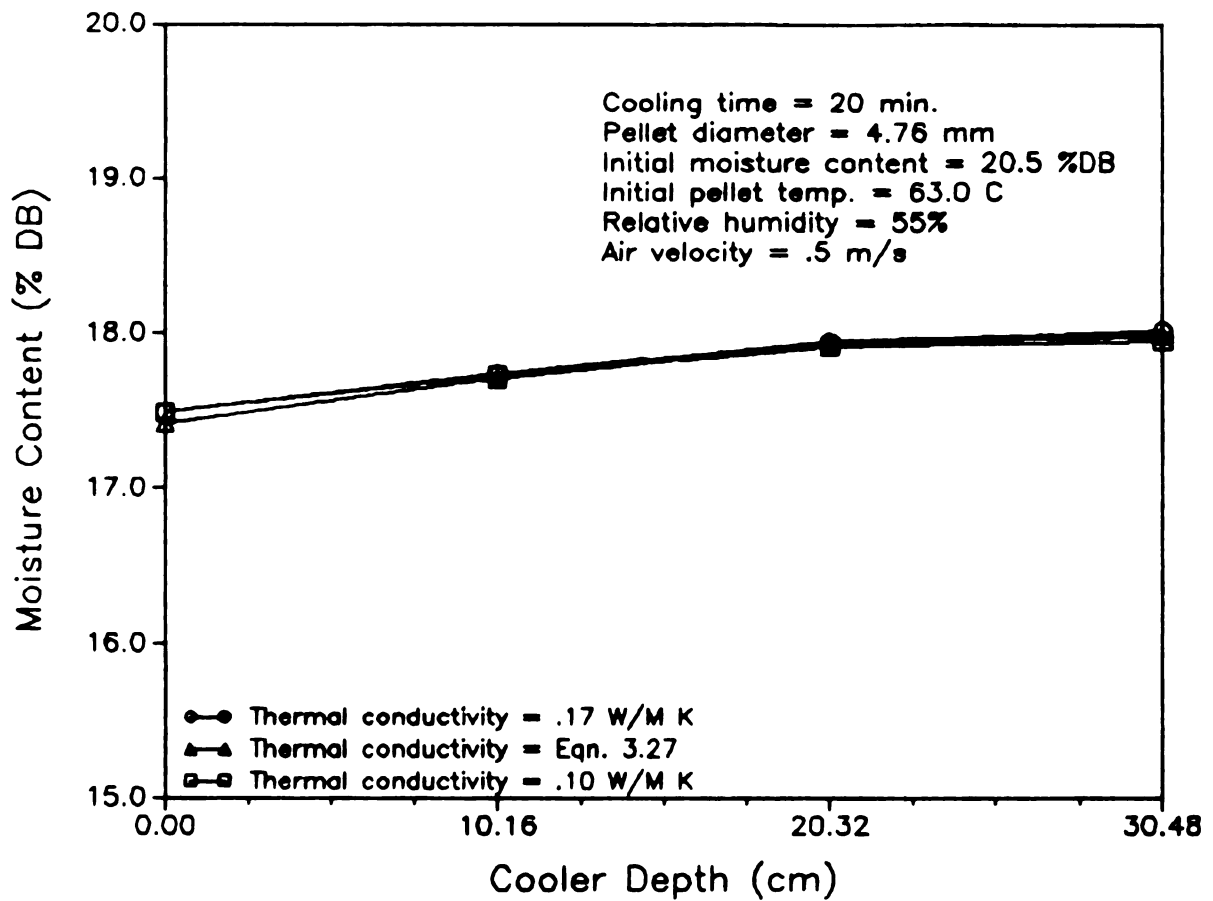


Fig. 6.32 Effect of thermal conductivity on the simulated moisture content of a fixed bed of pellets. Cooling air temperature 26.7 C.

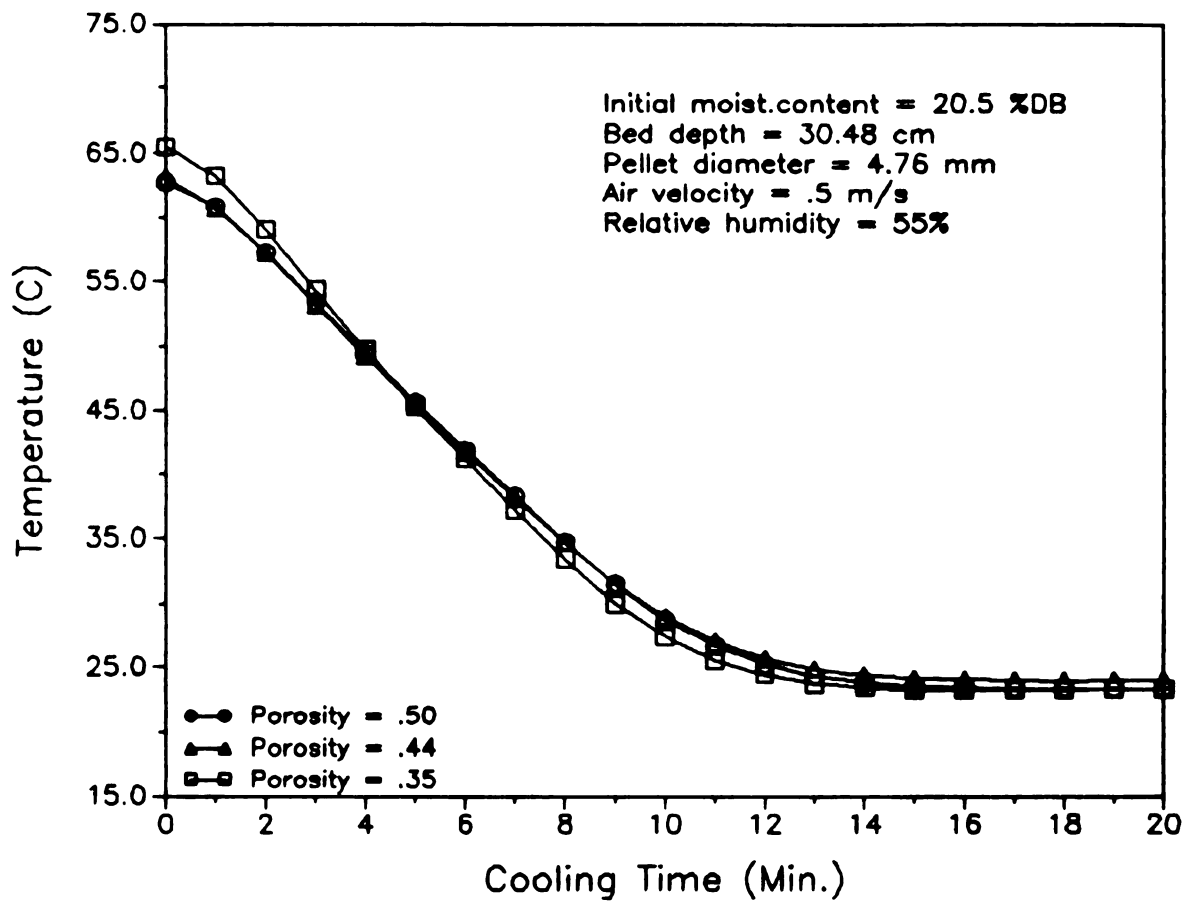


Fig. 6.33 Effect of bed porosity on the simulated temperatures at the top of fixed bed of pellets.
Cooling air temperature 26.7 C.

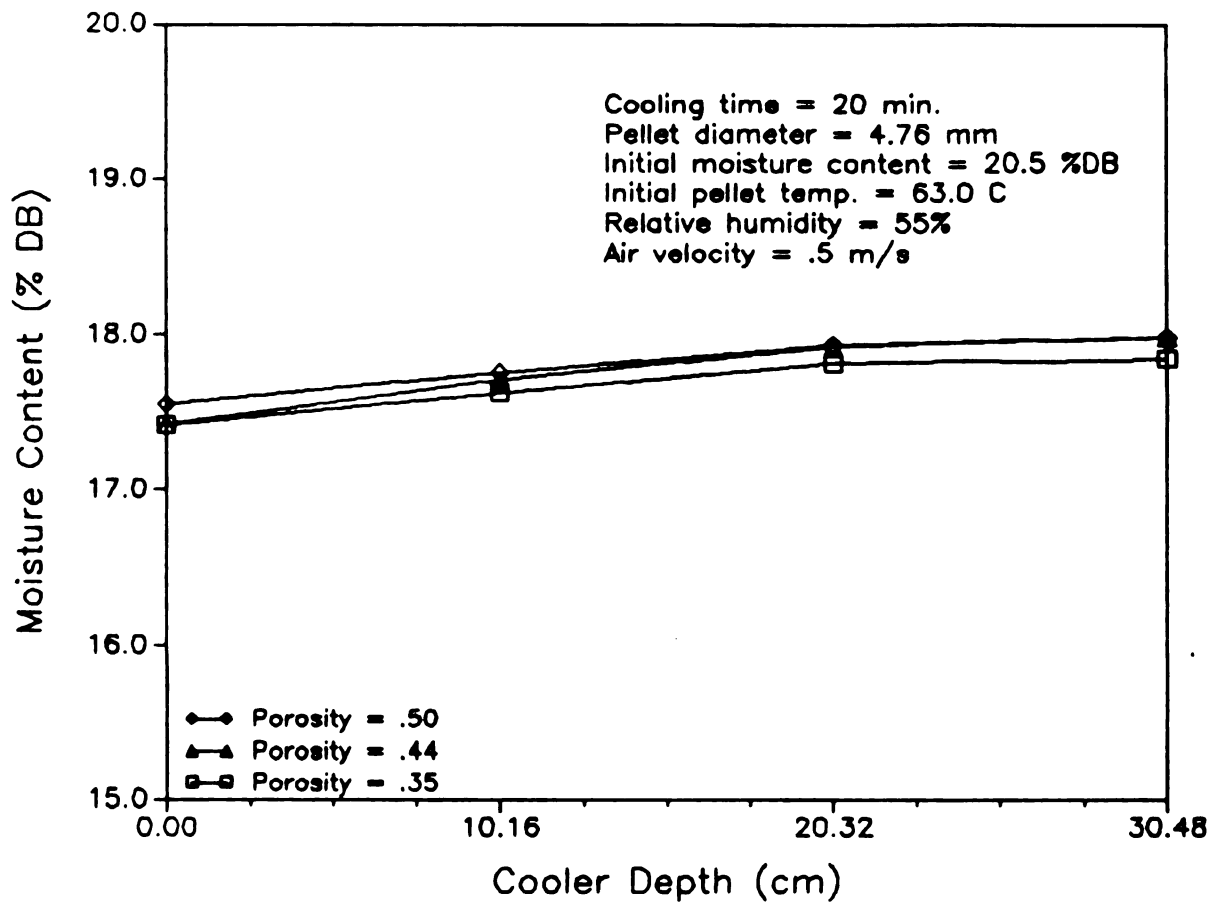


Fig. 6.34 Effect of bed porosity on the simulated moisture content of a fixed bed of pellets.
Cooling air temperature 26.7 C.

6.4 - Effects of Air Temperature, Relative Humidity, Air Velocity, Pellet Initial Moisture Content and Temperature, and Pellet Diameter

Table 6.10 shows the range of the inputs to the PDE model. The parameter values shown in Table 6.8 were used in this analysis.

Table 6.10 - Input Values to the Simulation PDE Model of a Fixed-Bed of Pellets Cooler.

Cooling air temperature (C)	21.1, 26.7, 32.2
Relative humidity (%)	40, 55, 70
Air velocity (m/s)	.5, .75
Initial pellet temperature (C)	48.9, 62.7, 71.1
Initial pellet moisture content (% DB)	16.3, 20.5
Pellet diameter (mm)	4.76, 6.35
Bed depth (cm)	30.48

Figures 6.35 and 6.36 illustrate the effect of the cooling air temperature on the pellet temperature and moisture content. A lower inlet air temperature results in faster cooling and a lower final temperature of the pellets, and in a higher moisture content.

The effect of relative humidity is shown in Figures 6.37 and 6.38. The higher relative humidities result in slightly higher pellet temperatures, but greatly affect the moisture content. For example, at the bottom of the cooler after 20 minutes of cooling, the moisture content is 16.5% DB at 40% relative humidity and 18.5% DB at 70%. At the top the difference in moisture content is about 1% and 2% at the bottom of the bed. The difference is smaller at the top of

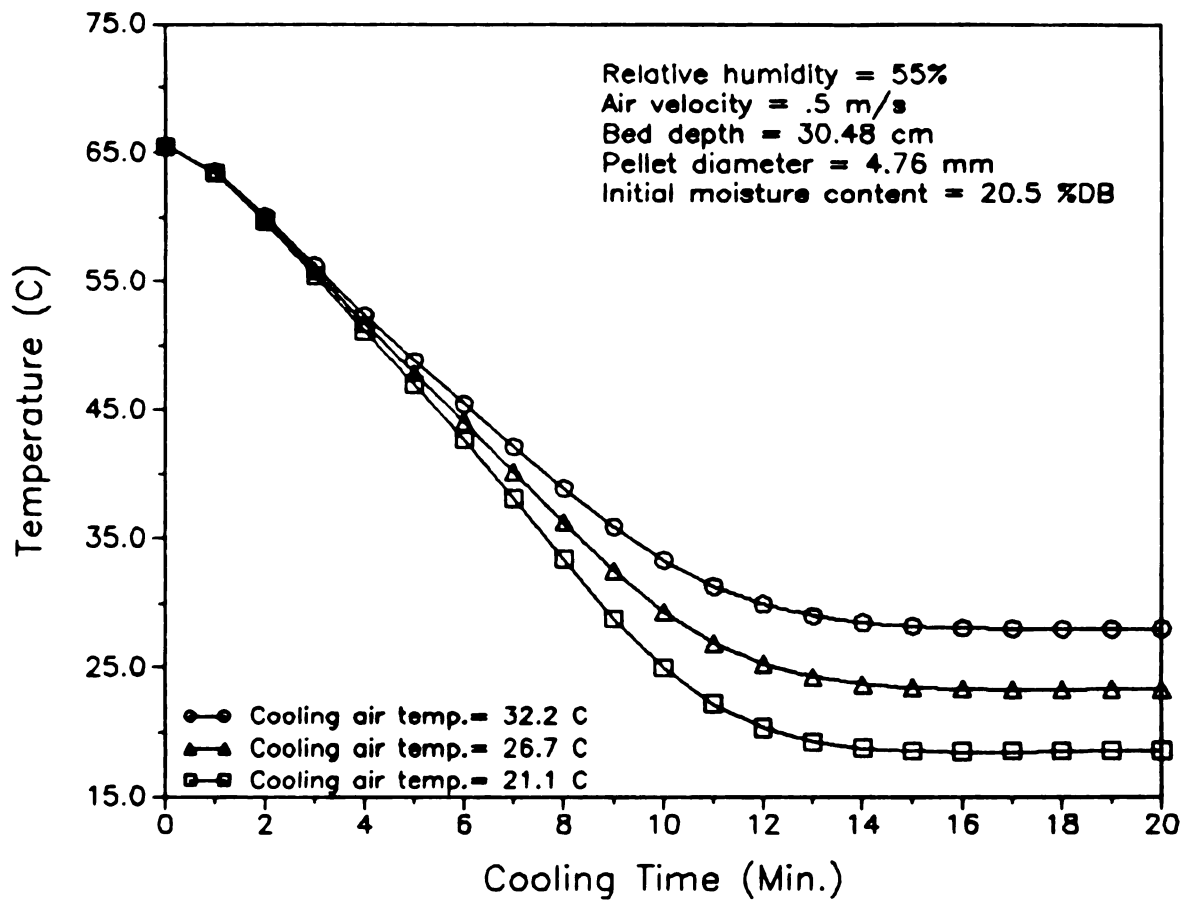


Fig. 6.35 Effect of cooling air temperature on the simulated temperatures at the top of a fixed bed of pellets.

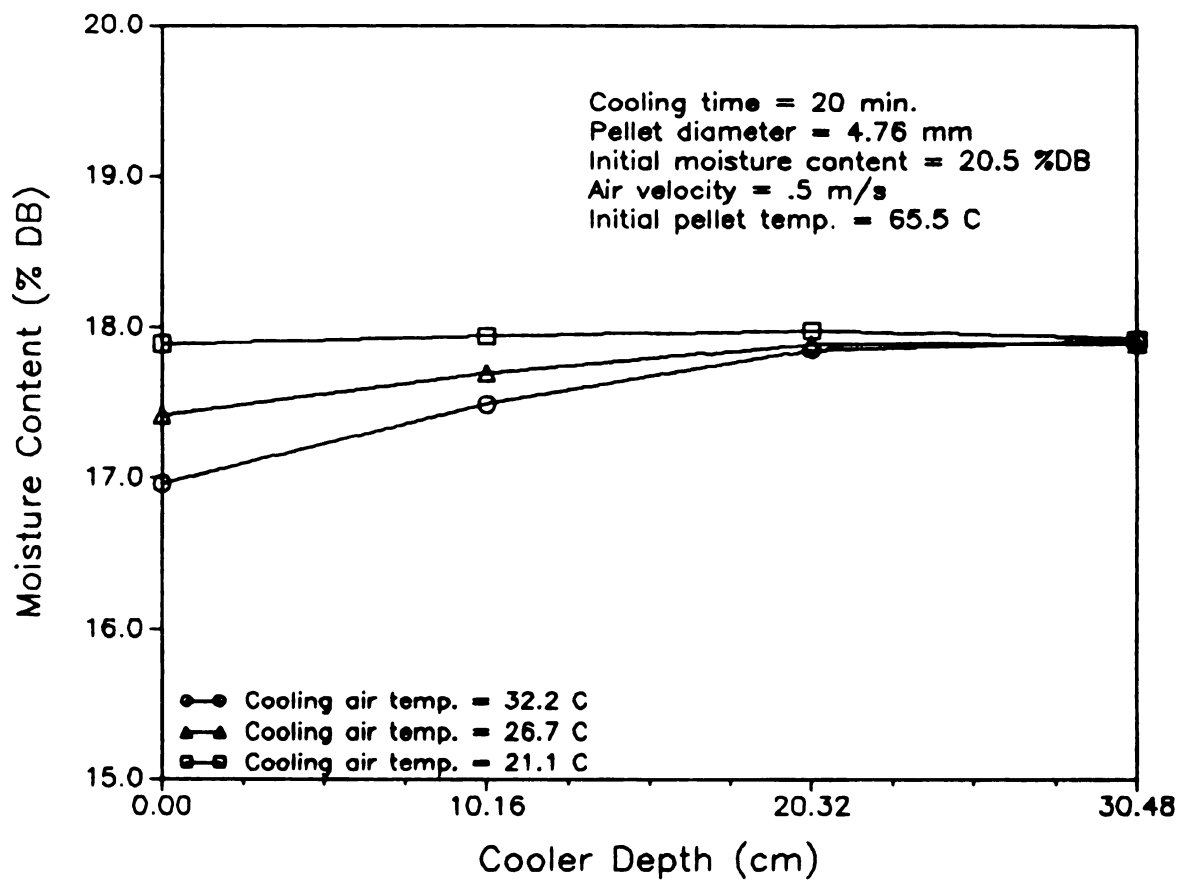


Fig. 6.36 Effect of cooling air temperature on the simulated moisture content of a fixed bed of pellets.

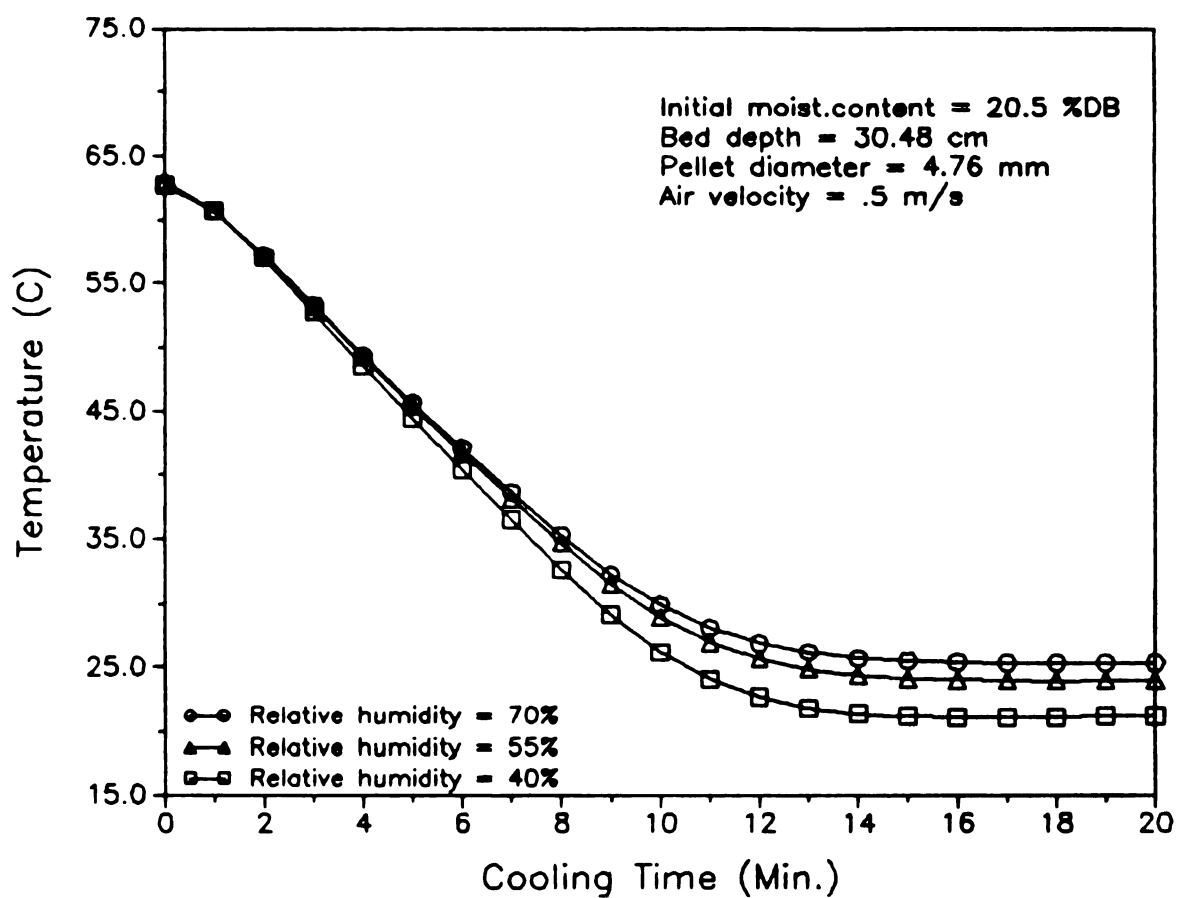


Fig. 6.37 Effect of relative humidity on the simulated temperatures at the top of fixed bed of pellets. Cooling air temperature 26.7 C.

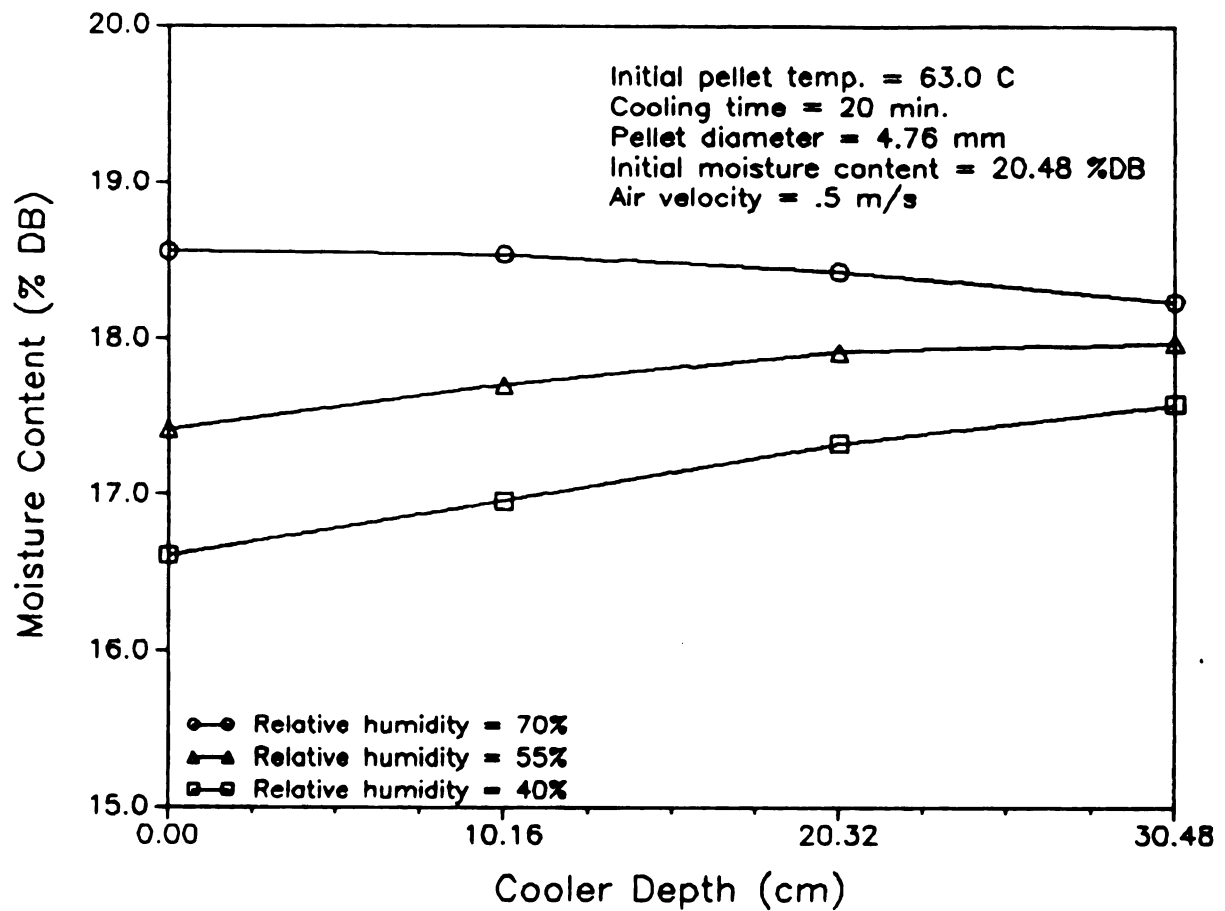


Fig. 6.38 Effect of relative humidity on the simulated moisture content of a fixed bed of pellets. Cooling air temperature 26.7 C.

the cooler than at the bottom because the air is heated by the pellets as it passes through the bed thereby increasing its drying potential.

Figures 6.39 and 6.40 show the effect of the air velocity on pellet temperature and moisture content. As expected, the higher air flow results in more rapid cooling. However, the faster cooling results in less pellet drying in 20 minutes.

The inlet pellet temperature effect is illustrated in Figures 6.41 and 6.42. Only during the first 10 minutes there is a difference in the pellet temperatures. After 10 minutes the pellet temperatures at the top of the bed have reached about the same temperature. The moisture content of the pellets is lower for the higher initial pellet temperature due to the dependence of pellet diffusivity on the pellet temperature.

Figures 6.43 and 6.44 show the effect of the initial pellet moisture content after 20 minutes cooling. The pellet temperature is not greatly affected in this range of initial moisture content. After 20 minutes of cooling the pellets with an initial moisture content of 20.5% DB at the bottom of the cooler had lost two percentage points while the pellets with 16.3% DB had lost only 1%.

The diameter of the pellets significantly affects the cooling rate as illustrated in Figures 6.45 and 6.46. As expected, the smaller diameter pellets cool faster than the larger ones. The moisture content of the small pellets is lower at the bottom of the cooler where the temperature of

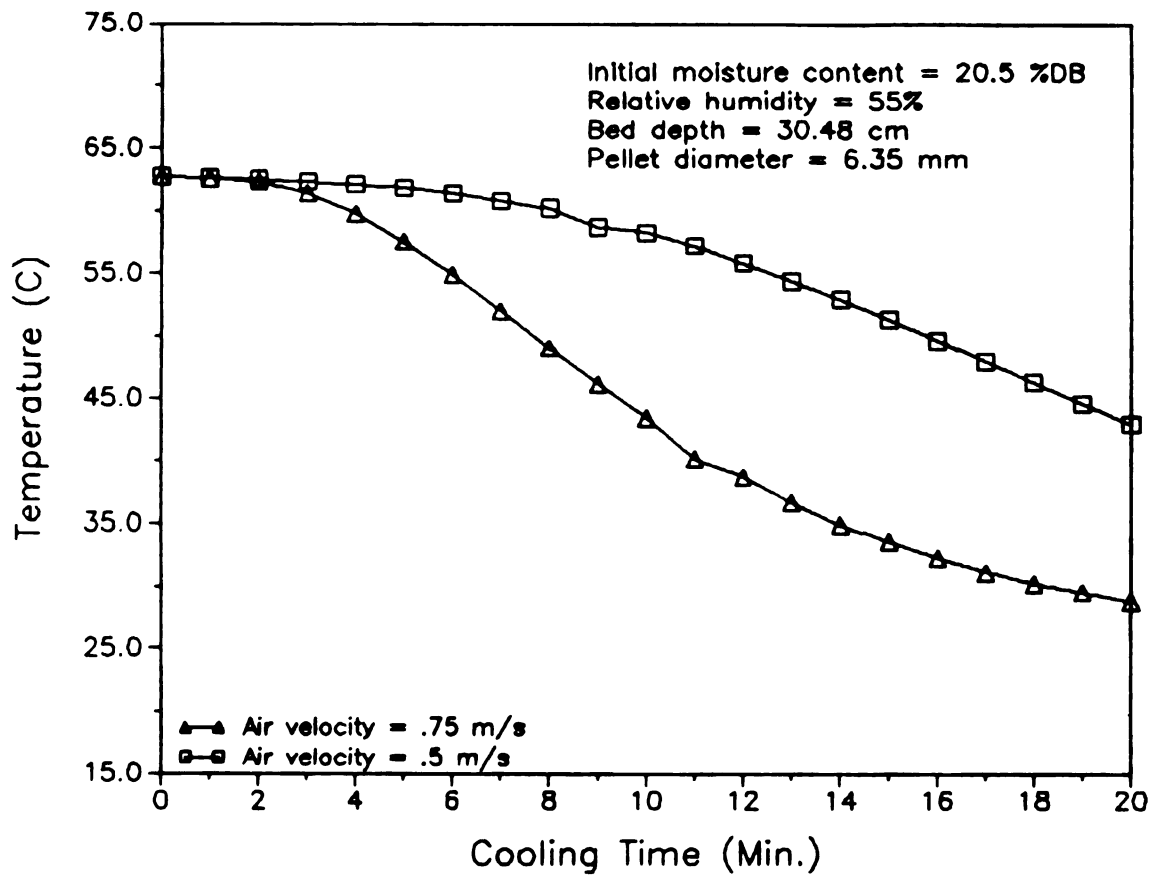


Fig. 6.39 Effect of air velocity on the simulated temperatures at the top of fixed bed of pellets.
Cooling air temperature 26.7 C.

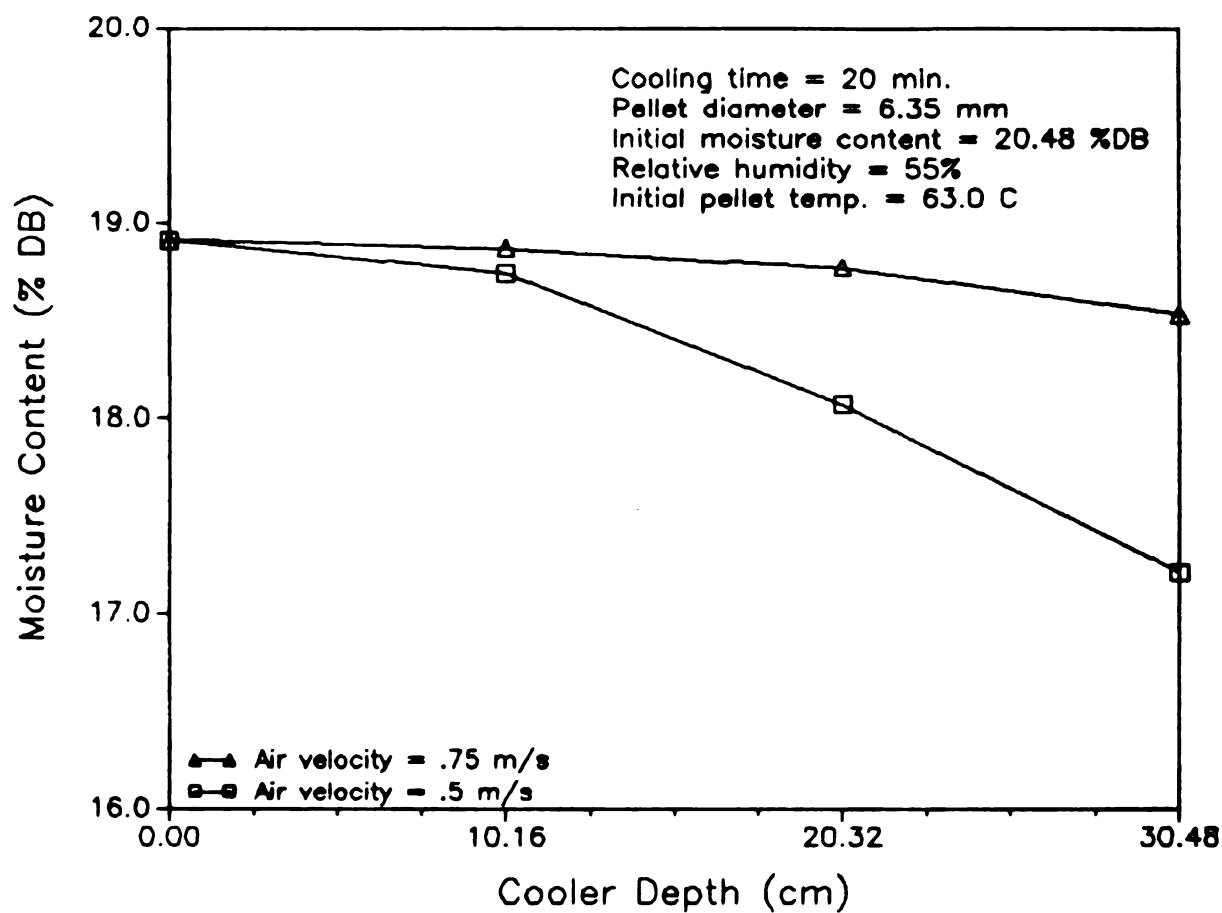


Fig.6.40 Effect of air velocity on the simulated moisture content of a fixed bed of pellets.
Cooling air temperature 26.7 C.

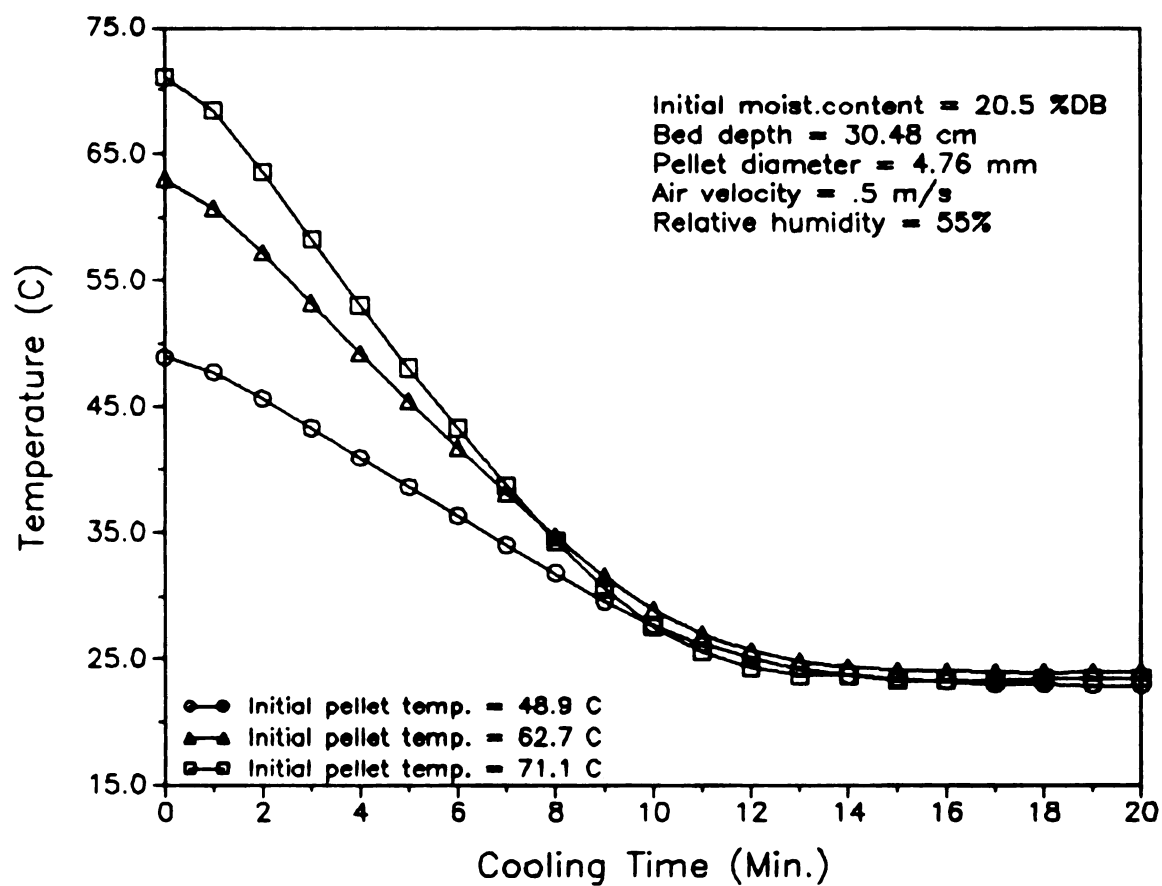


Fig. 6.41 Effect of initial pellet temperature on the simulated temperatures at the top of a fixed bed of pellets. Cooling air temperature 26.7 C.

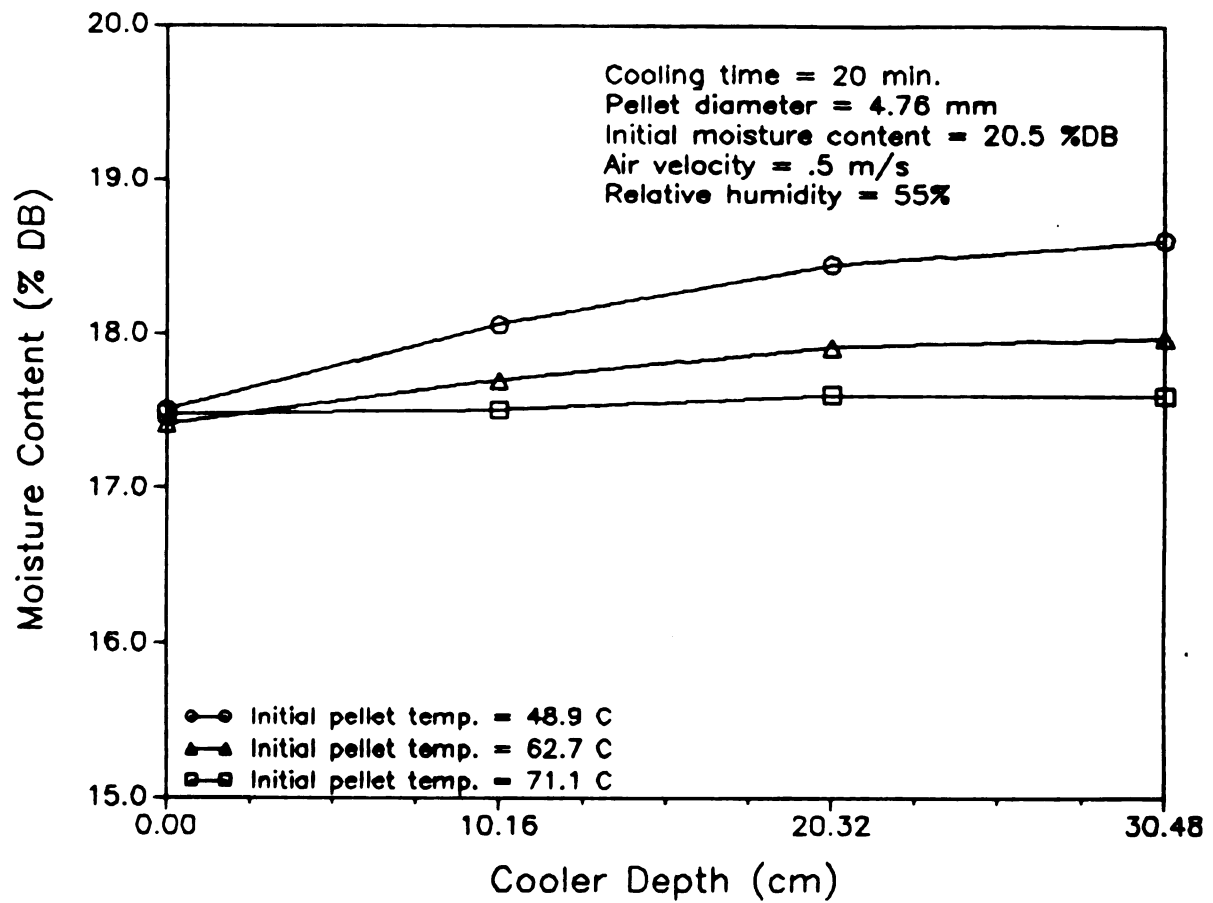


Fig. 6.42 Effect of initial pellet temperature on the simulated moisture content of a fixed bed of pellets. Cooling air temperature 26.7 C.

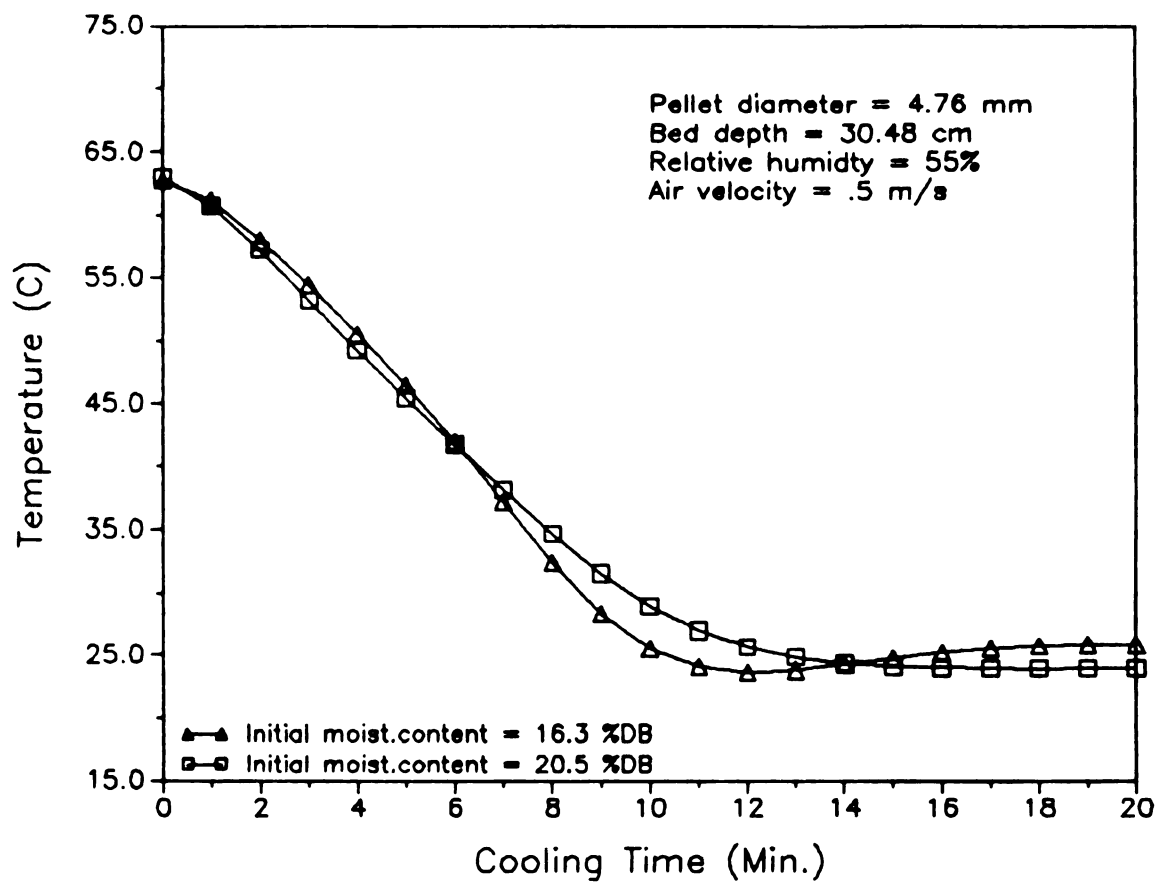


Fig.6.43 Effect of initial pellet moisture content on the simulated temperatures at the top of a fixed bed of pellets. Cooling air temp. 26.7 C.

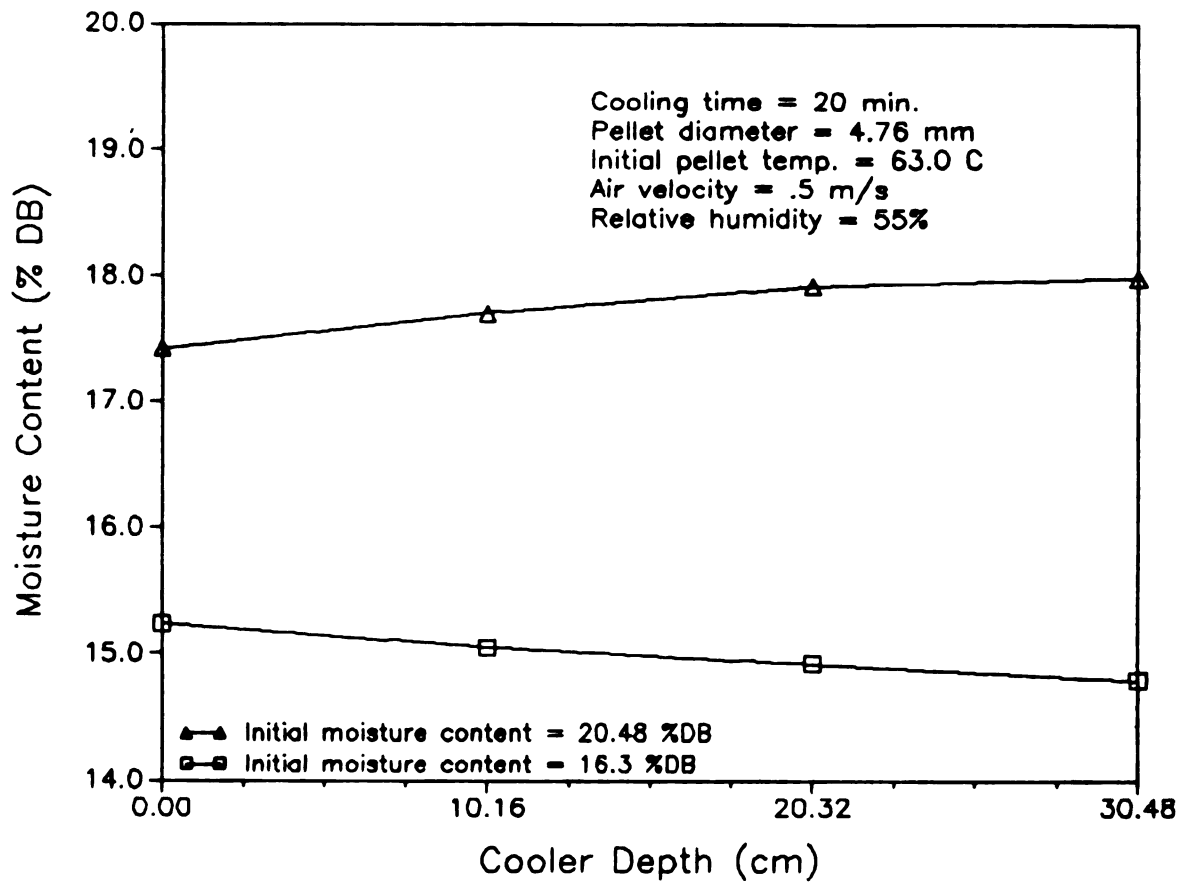


Fig. 6.44 Effect of initial pellet moisture content on the simulated moisture content of a fixed bed of pellets. Cooling air temp. 26.7 C.

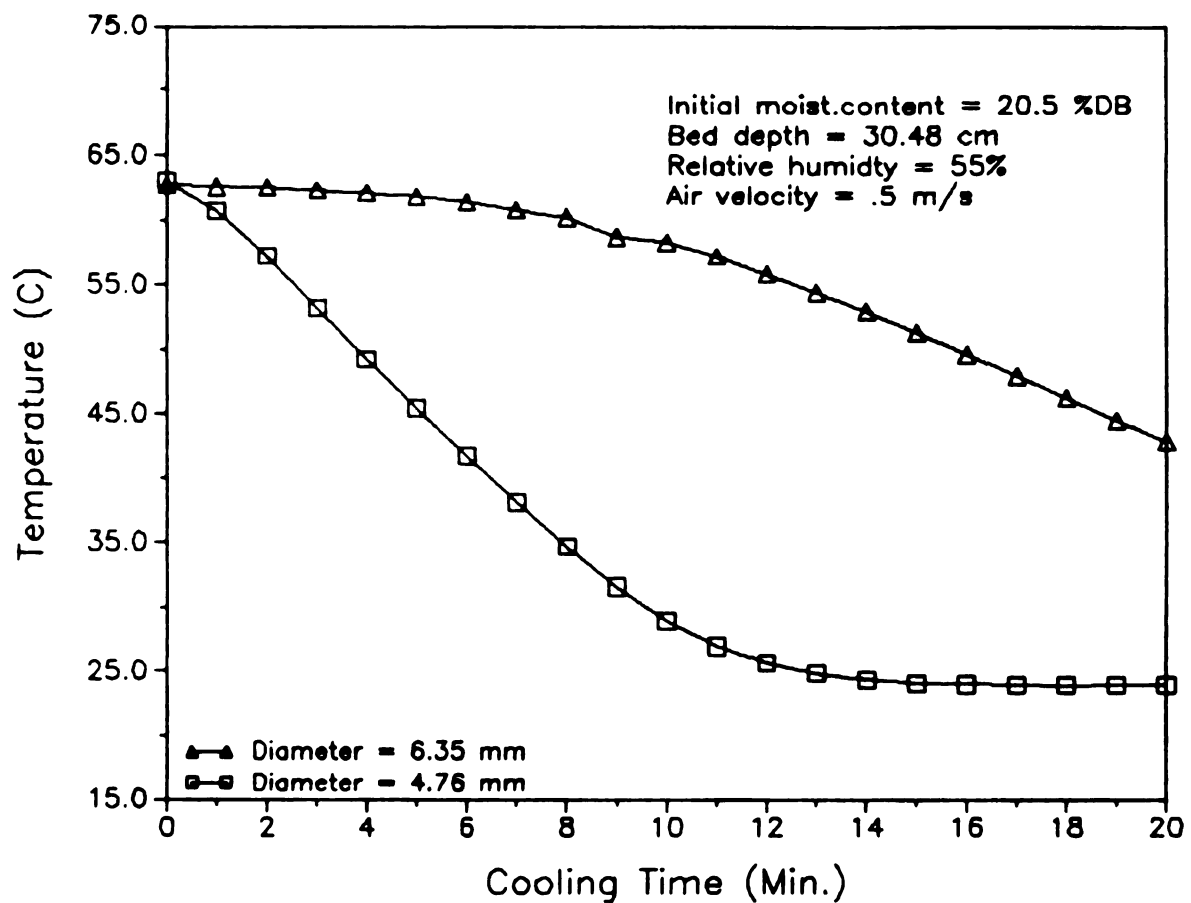


Fig. 6.45 Effect of pellet diameter on the simulated temperatures at the top of a fixed bed of pellets. Cooling air temperature 26.7 C.

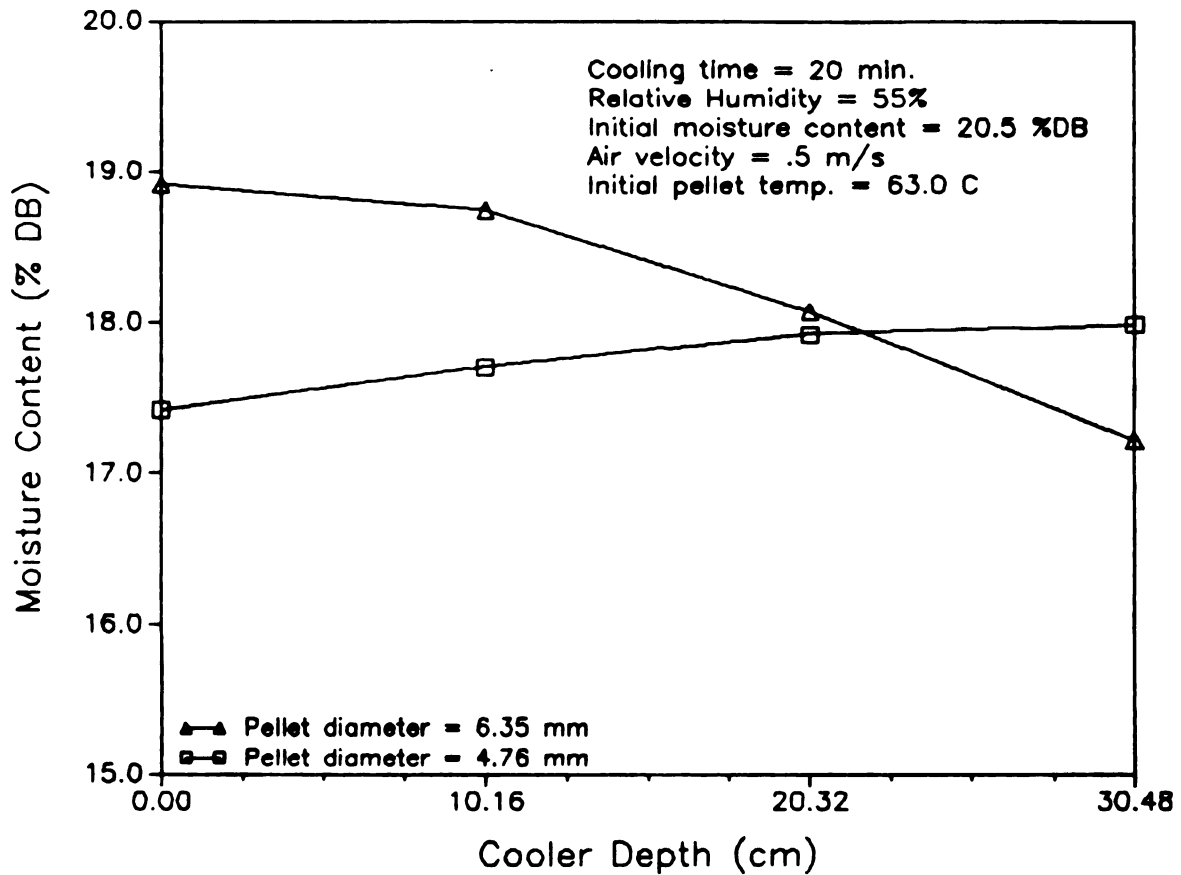


Fig. 6.46 Effect of pellet diameter on the simulated moisture content of a fixed bed of pellets. Cooling air temperature 26.7 C.

the small pellets equilibrates faster with the cooling air. At the top the larger diameter pellets have a low moisture content because they are about 20 C warmer than the small ones.

Figures 6.47 and 6.48 illustrate the temperature and moisture content gradients within a 4.76 mm and 6.35 mm diameter pellet, respectively. The figures show that the temperature gradients inside the pellets are negligible. The pellet temperatures at the top of the bed are lower than at the bottom due to evaporative cooling (see also Figure 6.15). The moisture content gradients within the pellets at the bottom of the bed are significant due to the higher temperatures and lower relative humidities at the bottom. Figure 6.48 shows that for the larger pellets (6.35 mm diameter) there is a significant moisture content gradient inside the pellets at the bottom and at the top of the bed during the cooling process. As shown in Figure 6.45, larger pellets cool slower than smaller pellets and have a higher temperature; this results in dryer pellets with a higher moisture content gradient at the top of the bed.

From the analysis in this section, it can conclude that the cooling air temperature and velocity, and the pellet diameter are the parameters that have a significant effect on the pellet temperature and moisture content; also that the relative humidity has a significant effect only on the pellet moisture content. Thus, these parameters should be measured accurately when performing a deep-bed cooling test.

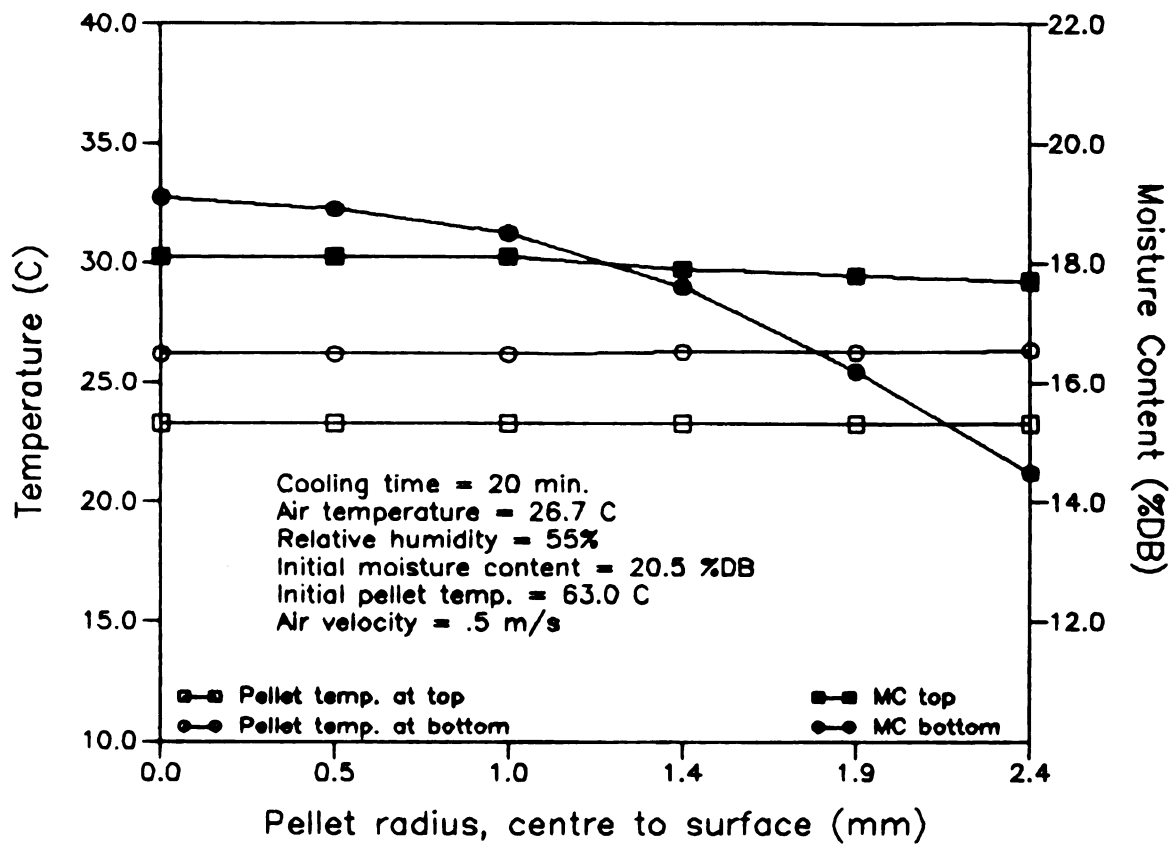


Fig. 6.47 Simulated temperature and moisture content gradients within a pellet.
 Pellet diameter 4.76 mm.

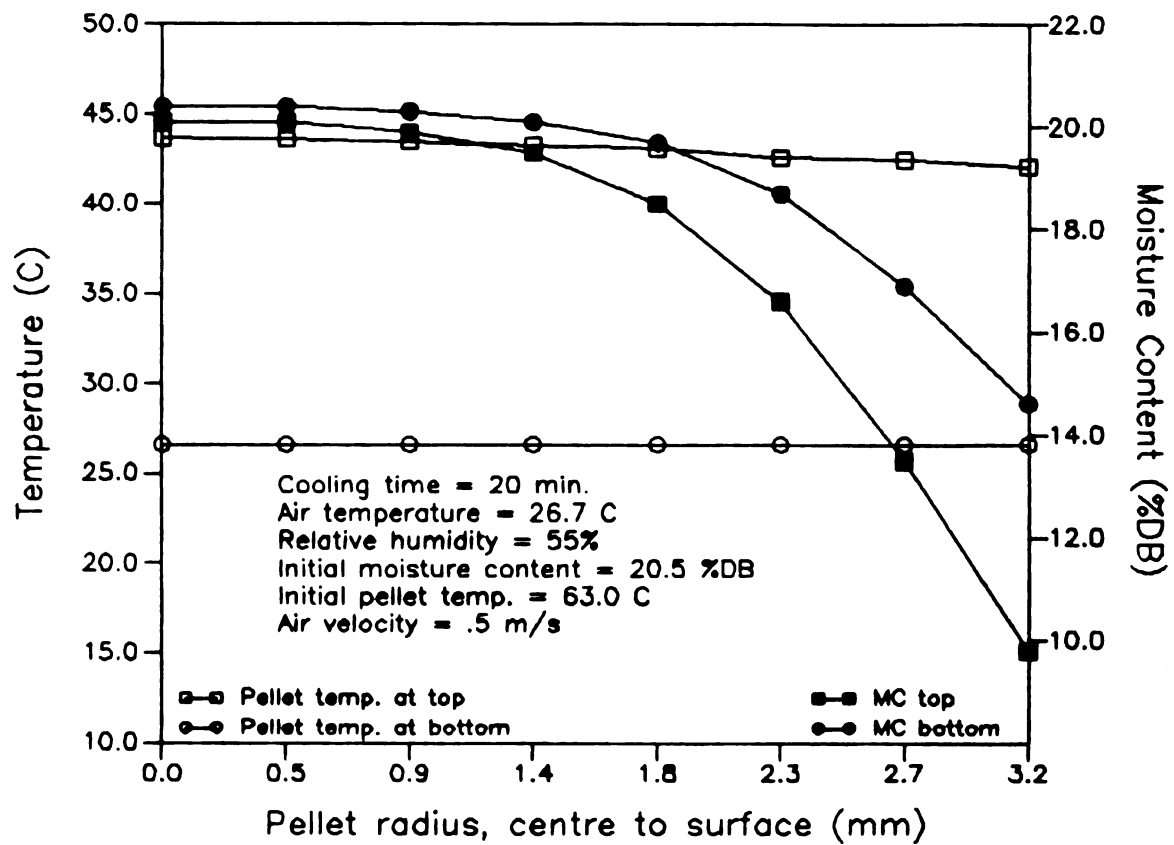


Fig. 6.48 Simulated temperature and moisture content gradients within a pellet.
 Pellet diameter 6.35 mm.

7 - SUMMARY AND CONCLUSIONS

The summary and conclusions of this study of deep-bed cooling of pellets are:

1. Thin-layer drying tests of feed pellets were conducted at 15.6 to 43.3 C (60 to 110 F), 40 to 70% relative humidity, and 18.1 to 19.1% DB moisture content.
2. The Chung-Pfost equilibrium moisture content equation for pellets best represents the equilibrium moisture content data.
3. An Arrhenius-type equation adequately describes the effect of temperature on the diffusion coefficient of feed pellets.
4. The heat and mass balance (HMB) and the partial differential (PDE) models for the cooling of pellets in a horizontal-belt cooler are both in acceptable agreement with the experimental data.
5. The PDE model requires between three to five minutes execution time on the IBM-AT, about ten times as long as the HMB model, to simulate one minute of cooling, but is more accurate than the HMB model.

6. The cooling air temperature and velocity significantly affect the final pellet temperature and moisture content in a horizontal-belt pellet cooler.
7. The relative humidity only slightly affects the pellet temperature but significantly influences the pellet moisture content in a horizontal-belt pellet cooler.
8. The pellet diameter greatly affects the cooling and drying rate of feed pellets in a horizontal-belt pellet cooler.
7. The sensitivity analysis of the horizontal-belt pellet cooler model shows that the initial pellet moisture content has a minor influence on the final pellet temperature; however, the initial pellet temperature has a significant influence on the final pellet moisture content.
10. The heat transfer coefficient, the specific heat, and density are the pellet properties significantly affecting the final pellet temperature and moisture content in a horizontal-belt pellet cooler.

8 - SUGGESTIONS FOR FUTURE RESEARCH

Additional research remains to be carried out in the following areas:

1. To develop the equilibrium moisture content for different feed-pellet types.
2. To evaluate the dependence of pellet moisture content and density on the feed-pellet diffusion coefficient.
3. To determine the heat and mass transfer coefficients, the specific heat, and the thermal conductivity of different types of feed-pellets.
4. To investigate the horizontal-belt cooling of different pellet types.
5. To investigate the influence of the cooling air temperature, velocity, and relative humidity on the pellet temperature and moisture content in different pellet-cooler types (i.e. counterflow cooler, crossflow cooler).

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APPENDICES

Appendix A - Experimental Results

Appendix B - Psychrometric Chart and Output Sample

Appendix C - Heat and Mass Balance Model and Output Sample

**Appendix D - Partial Differential Equations Model and Output
Sample**

Appendix E - BMDPAR subroutine: EMC and D Estimation

APPENDIX A

EXPERIMENTAL RESULTS

EXPERIMENTAL RESULTS

Test 1

Table A.1 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 21.1 C, RH 55%, Air Velocity .5 m/s.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	71.4	71.5	72.3	71.8	71.6	72.8	72.6
1	29.6	47.0	52.0	54.3	57.6	60.4	62.4
2	28.8	38.5	43.7	45.5	48.3	50.6	52.1
3	26.9	33.8	38.6	40.4	42.7	44.6	45.9
4	25.4	30.6	34.7	36.8	39.0	40.6	41.6
5	24.3	28.1	31.8	33.7	35.8	37.4	38.6
6	23.6	26.1	29.2	31.1	33.2	34.6	35.8
7	23.2	24.6	27.1	28.9	30.9	32.3	33.4
8	22.6	23.4	25.6	27.2	29.1	30.5	31.6
9	22.4	22.6	24.2	25.6	27.4	28.7	29.8
10	22.0	21.8	23.1	24.2	25.6	27.1	28.2
11	21.7	21.3	22.2	23.2	24.6	25.9	26.9
12	21.6	21.0	21.6	22.3	23.6	24.8	25.8
13	21.4	20.7	21.0	21.6	22.7	23.6	24.7
14	21.2	20.4	20.6	21.1	22.0	22.9	23.8
15	21.2	20.2	20.2	20.6	21.3	22.2	23.1
16	21.2	20.2	20.1	20.3	20.9	21.6	22.4
17	21.2	20.1	19.9	20.1	20.5	21.1	21.8
18	21.1	20.1	19.7	19.8	20.2	20.7	21.3
19	21.1	20.1	19.7	19.7	19.9	20.3	20.9
20	21.1	20.1	19.7	19.6	19.8	20.2	20.6

Initial moisture content = 20.7 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Test 2

Table A.2 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 21.1 C, RH 55%, Air Velocity .1 m/s.

Cooling Time (min)	Cooler						
	Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	62.2	62.8	62.5	63.2	63.4	63.9	63.7
1	28.1	51.2	54.2	58.6	60.3	62.3	64.0
2	25.7	41.7	45.1	49.6	53.5	56.1	58.4
3	25.9	36.5	39.9	43.6	47.3	50.2	52.3
4	25.5	33.4	36.4	39.6	42.8	45.3	47.6
5	24.8	31.3	34.1	36.8	39.6	41.9	43.7
6	24.0	29.5	32.2	34.5	37.0	39.1	40.6
7	23.4	28.0	30.5	32.6	34.9	36.7	38.1
8	23.0	26.7	29.1	31.1	33.2	34.8	36.1
9	22.7	25.6	27.8	29.8	31.7	33.2	34.4
10	22.3	24.6	26.6	28.5	30.2	31.6	32.8
11	22.1	23.7	25.6	27.4	29.1	30.3	31.4
12	21.9	23.1	24.8	26.5	28.0	29.3	30.3
13	21.7	22.5	24.1	25.7	27.1	28.2	29.2
14	21.6	22.0	23.3	24.9	26.3	27.3	28.2
15	21.5	21.6	22.8	24.2	25.4	26.4	27.3

Initial moisture content = 20.7 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Test 5

Table A.3 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 32.2 C, RH 55%, Air Velocity .5 m/s.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	71.2	73.7	73.3	72.4	71.6	73.4	73.3
1	36.8	51.3	54.8	56.4	59.1	62.1	64.0
2	34.9	42.6	46.2	47.0	49.4	52.3	53.9
3	33.9	38.0	41.2	42.7	43.9	46.3	47.8
4	33.2	35.4	38.1	39.6	40.5	42.4	43.7
5	32.9	33.6	35.7	37.1	37.8	39.6	40.6
6	32.8	32.6	33.9	35.2	35.9	37.4	38.3
7	32.7	32.0	32.8	33.9	34.6	35.7	36.6
8	32.6	31.4	32.0	32.8	33.3	34.3	35.1
9	32.8	31.3	31.5	32.1	32.4	33.3	33.9
10	32.8	31.2	31.1	31.4	31.8	32.5	33.1
11	32.9	31.2	30.8	31.1	31.3	31.9	32.4
12	33.0	31.1	30.7	30.8	30.9	31.3	31.7
13	33.0	31.2	30.6	30.5	30.6	30.9	31.3
14	33.0	31.2	30.5	30.3	30.3	30.6	30.9
15	33.0	31.3	30.5	30.3	30.2	30.4	30.6
16	33.0	31.3	30.4	30.1	30.0	30.2	30.4
17	33.1	31.4	30.4	30.1	30.0	30.1	30.2
18	33.1	31.4	30.4	30.0	29.9	29.8	30.0
19	33.2	31.4	30.4	29.9	29.7	29.7	29.9
20	33.0	31.4	30.5	29.9	29.7	29.6	29.7

Initial moisture content = 19.1 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673Kg/m³, Bed depth = 30.48 cm

Test 6

Table A.4 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 32.2 C, RH 55%, Air Velocity .1 m/s.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	65.3	65.3	67.5	67.8	67.9	68.4	68.2
1	36.7	50.8	56.2	60.5	63.2	65.4	67.1
2	34.5	42.7	47.4	50.9	54.8	57.6	59.9
3	33.8	38.7	42.7	45.3	48.7	51.4	53.7
4	33.6	36.2	39.7	41.9	44.6	47.0	49.2
5	33.3	34.7	37.4	39.3	41.5	43.6	45.6
6	33.2	33.6	35.8	37.3	39.2	40.9	42.8
7	33.1	32.7	34.5	35.8	37.3	39.0	40.6
8	32.9	32.1	33.4	34.7	35.9	37.4	38.8
9	32.8	31.7	32.7	33.7	34.7	36.2	37.4
10	32.8	31.3	32.1	33.0	33.8	35.0	36.2
11	32.7	31.1	31.5	32.3	33.1	34.2	35.2
12	32.6	30.9	31.1	31.8	32.4	33.4	34.4
13	32.6	30.7	30.7	31.3	31.9	32.7	33.6
14	32.5	30.5	30.3	30.9	31.4	32.1	32.8
15	32.7	30.5	30.1	30.4	30.8	31.8	32.2
16	32.8	30.6	30.0	30.3	30.7	31.3	31.9
17	32.8	30.5	29.8	30.1	30.4	30.9	31.4
18	32.9	30.5	29.6	29.6	30.1	30.6	31.1
19	32.9	30.5	29.6	29.7	29.9	30.4	30.8
20	32.8	30.5	29.4	29.4	29.7	30.1	30.5

Initial moisture content = 19.1 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Test 7

Table A.5 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 17.7 C, RH 70%, Air Velocity .5 m/s.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	67.6	70.0	70.5	69.4	68.5	70.2	70.9
1	23.2	44.5	50.6	52.6	55.3	57.1	59.2
2	23.8	35.3	41.9	44.9	47.1	48.6	50.3
3	22.6	30.2	36.0	39.6	41.6	42.9	44.3
4	21.4	27.1	31.9	35.5	37.6	39.1	40.3
5	20.3	24.8	28.6	32.1	34.5	36.0	37.3
6	19.7	23.1	26.4	29.5	31.6	33.3	34.7
7	19.3	21.5	24.3	27.2	29.3	31.0	32.3
8	19.0	20.3	22.7	25.2	27.2	28.9	30.3
9	18.7	19.4	21.4	23.6	25.5	27.2	28.7
10	18.4	18.7	20.2	22.2	23.8	25.6	27.0
11	18.2	18.2	19.3	21.0	22.4	24.1	25.6
12	18.1	17.7	18.6	20.0	21.3	22.7	24.2
13	17.9	17.4	18.1	19.2	20.4	21.7	23.1
14	17.8	17.2	17.7	18.6	19.5	20.7	22.1
15	17.6	16.9	17.2	17.9	18.8	19.8	21.1
16	17.4	16.8	16.9	17.5	18.2	19.1	20.2
17	17.3	16.6	16.7	17.1	17.7	18.5	19.5
18	17.2	16.6	16.6	16.9	17.3	18.1	18.9
19	17.2	16.4	16.3	16.6	17.0	17.6	18.4
20	17.1	16.3	16.3	16.4	16.7	17.3	17.9

Initial moisture content = 19.6 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Test 8

Table A.6 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 17.7 C, RH 70%, Air Velocity .1 m/s.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	60.3	61.2	60.0	61.6	62.4	62.4	62.6
1	23.9	45.3	50.1	53.3	56.4	58.3	59.3
2	22.4	36.6	42.9	45.8	49.1	51.5	52.5
3	22.4	31.9	38.6	41.4	44.2	46.4	47.6
4	21.9	28.8	35.1	38.1	40.5	42.4	43.7
5	21.2	26.7	32.4	35.4	37.6	39.4	40.6
6	20.4	25.1	30.1	33.2	35.3	36.9	38.2
7	19.8	23.7	28.2	31.3	33.4	34.9	36.2
8	19.4	22.5	26.6	29.6	31.6	33.1	34.4
9	19.1	21.5	25.2	28.1	30.1	31.6	32.8
10	18.7	20.6	24.1	26.8	28.8	30.3	31.4
11	18.5	20.0	22.9	25.6	27.5	28.9	30.1
12	18.2	19.3	21.9	24.5	26.3	27.7	28.9
13	18.1	18.8	21.1	23.4	25.3	26.7	27.8
14	17.9	18.4	20.3	22.6	24.3	25.8	26.9
15	17.8	18.0	19.7	21.7	23.4	24.8	26.0
16	17.7	17.7	19.1	21.1	22.6	23.9	25.1
17	17.5	17.4	18.7	20.3	21.6	23.1	24.3
18	17.4	17.2	18.2	19.8	21.2	22.4	23.5
19	17.2	17.0	17.9	19.3	20.6	21.8	22.9
20	17.1	16.7	17.5	18.8	20.1	21.2	22.2

Initial moisture content = 19.6 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Test 9

Table A.7 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 21.1 C, RH 70%, Air Velocity .5 m/s.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	61.1	62.4	64.4	63.9	62.1	64.6	64.6
1	26.7	46.8	50.4	51.9	54.4	56.4	57.9
2	24.5	37.4	42.8	44.5	46.8	48.3	49.6
3	23.9	32.1	37.8	40.1	41.6	42.8	43.9
4	23.5	28.8	33.8	36.4	38.1	39.1	40.1
5	23.3	27.1	30.9	33.6	35.3	36.4	37.3
6	23.2	26.1	29.1	31.6	33.3	34.2	35.2
7	23.0	25.3	27.7	29.8	31.4	32.4	33.3
8	22.9	24.8	26.7	28.5	29.9	31.0	31.8
9	22.8	24.3	26.1	27.4	28.8	29.7	30.6
10	22.8	24.1	25.6	26.8	28.0	28.8	29.6
11	22.8	23.9	25.2	26.3	27.3	28.0	28.8
12	22.7	23.7	24.8	25.8	26.7	27.3	28.0
13	22.7	23.5	24.5	25.4	26.2	26.7	27.4
14	22.6	23.4	24.3	25.2	25.9	26.4	27.1
15	22.6	23.3	24.2	24.9	25.6	26.1	26.6
16	22.6	23.3	24.0	24.7	25.3	25.8	26.3
17	22.6	23.2	23.9	24.6	25.2	25.5	26.0
18	22.6	23.1	23.8	24.4	25.0	25.3	25.8
19	22.5	23.1	23.7	24.3	24.8	25.1	25.6
20	22.6	23.0	23.6	24.2	24.7	25.1	25.4

Initial moisture content = 19.8 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Test 10

Table A.8 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 21.1 C, RH 70%, Air Velocity .1 m/s.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	58.5	58.7	58.4	58.4	58.6	59.9	59.1
1	26.9	46.4	50.8	53.2	55.8	57.1	58.3
2	24.9	38.9	43.7	46.4	49.9	52.1	54.1
3	24.4	34.2	39.1	41.7	44.8	47.1	48.9
4	24.3	31.3	35.8	38.4	41.0	43.1	44.8
5	24.1	29.5	33.5	36.0	38.3	40.2	41.8
6	24.1	28.2	31.7	34.0	36.1	37.8	39.3
7	23.9	27.4	30.3	32.5	34.3	35.7	37.5
8	23.7	26.7	29.2	31.3	32.8	34.1	35.5
9	23.7	26.2	28.4	30.3	31.7	32.9	34.2
10	23.6	25.8	27.7	29.3	30.6	31.7	32.9
11	23.6	25.6	27.3	28.7	29.8	30.8	31.9
12	23.5	25.3	26.8	28.1	29.1	30.0	30.9
13	23.4	25.1	26.5	27.7	28.6	29.3	30.3
14	23.3	24.8	26.1	27.3	28.0	28.7	29.6
15	23.3	24.7	25.9	26.9	27.6	28.2	29.0
16	23.3	24.4	25.7	26.6	27.2	27.8	28.5
17	23.3	24.4	25.5	26.3	26.9	27.4	28.2
18	23.2	24.3	25.3	26.1	26.7	27.2	27.7
19	23.2	24.2	25.1	25.9	26.4	26.9	27.4
20	23.2	24.1	24.9	25.8	26.2	26.6	27.1

Initial moisture content = 19.8 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Test 11

Table A.9 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 26.7 C, RH 70%, Air Velocity .5 m/s.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	64.8	67.1	68.4	65.2	65.1	65.5	64.4
1	30.4	46.2	50.9	55.1	57.9	60.2	62.1
2	28.8	38.1	42.6	45.9	47.8	51.8	53.3
3	28.1	33.9	38.2	40.7	42.0	45.6	46.9
4	27.6	31.8	35.3	37.7	38.6	41.3	42.7
5	27.2	30.6	33.4	35.4	36.2	38.3	39.4
6	26.9	29.7	32.1	33.8	34.4	36.1	37.1
7	26.7	29.1	31.2	32.7	33.3	34.6	35.4
8	26.7	28.8	30.5	31.8	32.3	33.3	34.0
9	26.6	28.4	29.9	31.2	31.6	32.3	32.9
10	26.6	28.1	29.6	30.7	31.1	31.6	32.1
11	26.6	27.9	29.3	30.3	30.7	31.1	31.5
12	26.5	27.8	29.1	30.0	30.3	30.7	31.1
13	26.6	27.6	28.8	29.7	30.1	30.3	30.6
14	26.6	27.5	28.9	29.5	29.8	30.0	30.3
15	26.6	27.4	28.4	29.3	29.6	29.8	30.0
16	26.6	27.3	28.3	29.2	29.4	29.6	29.8
17	26.6	27.3	28.2	28.9	29.3	29.4	29.6
18	26.6	27.2	28.2	28.8	29.2	29.3	29.4
19	26.6	27.2	28.2	28.8	29.2	29.3	29.4
20	26.6	27.1	27.9	28.6	28.9	29.1	29.2

Initial moisture content = 20.5 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Test 12

Table A.10 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 26.7 C, RH 70%, Air Velocity .1 m/s.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	58.3	59.7	59.7	59.5	60.6	61.5	61.4
1	31.4	47.4	53.3	56.6	58.1	59.5	61.4
2	29.1	39.7	45.3	49.4	52.3	54.8	57.9
3	28.5	35.8	40.3	44.1	47.1	49.8	53.4
4	28.1	33.7	37.2	40.4	43.1	45.7	49.4
5	27.8	32.3	35.1	37.7	40.1	42.4	45.8
6	27.5	31.4	33.6	35.7	37.8	39.7	42.8
7	27.2	30.7	32.6	34.2	35.9	37.7	40.6
8	27.3	30.2	31.9	33.2	34.7	36.1	38.6
9	27.1	29.8	31.3	32.4	33.6	34.7	36.9
10	27.3	29.6	30.8	31.7	32.7	33.8	35.7
11	27.3	29.3	30.5	31.2	31.9	32.9	34.5
12	27.3	29.2	30.2	30.9	31.4	32.2	33.6
13	27.2	28.9	30.0	30.5	31.1	31.7	32.9
14	27.0	28.7	29.7	30.3	30.7	31.3	32.3
15	26.8	28.4	29.5	30.0	30.3	30.9	31.7

Initial moisture content = 20.5 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Test 13

Table A.11 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 21.1 C, RH 55%, Air Velocity .1 m/s.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	68.7	69.8	68.5	69.2	68.7	68.8	71.4
1	29.4	52.6	64.3	65.2	67.9	68.2	69.2
2	26.1	42.5	55.2	62.4	63.8	65.3	67.8
3	25.7	36.9	47.8	55.9	57.9	60.2	63.8
4	25.4	33.8	42.4	50.4	52.8	55.3	59.3
5	24.8	31.7	38.2	45.4	47.9	50.7	54.7
6	24.3	30.2	35.2	41.6	44.1	46.8	50.9
7	23.7	29.0	32.9	38.5	40.7	43.4	47.3
8	23.2	28.0	31.3	36.1	38.2	40.8	44.4
9	22.7	27.0	30.0	34.0	36.0	38.5	41.7
10	22.3	26.0	28.8	32.4	34.1	36.4	39.4
11	21.9	25.1	27.7	31.0	32.6	34.7	37.4
12	21.7	24.3	26.8	29.8	31.2	33.3	35.7
13	21.4	23.6	26.0	28.7	29.9	31.9	34.2
14	21.2	22.9	25.2	27.7	28.9	30.7	32.8
15	21.2	22.5	24.5	26.9	28.0	29.7	31.8
16	21.1	22.1	23.9	26.1	27.1	28.7	30.7
17	20.9	21.7	23.4	25.4	26.3	27.8	29.6
18	21.1	21.3	22.8	24.8	25.6	27.3	28.8
19	21.1	21.1	22.4	24.2	24.9	26.3	28.0
20	21.1	20.8	22.1	23.7	24.3	25.7	27.2

Initial moisture content = 18.1 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Test 14

Table A.12 - Experimental Values of the Air Temperatures Between the Pellets (C) in a Deep-Bed Cooling Test. Cooling Air Temperature 21.1 C, RH 55%, Air Velocity .5 m/s.

Cooling Time (min)	Cooler Depth (cm)						
	0.00	5.08	10.16	15.24	20.32	25.40	30.48
0	62.2	63.3	63.3	63.7	63.6	63.5	63.8
1	27.6	45.3	52.8	58.4	62.3	60.8	62.6
2	27.1	36.7	42.0	47.4	53.2	52.9	54.7
3	26.3	33.2	36.9	40.8	45.6	46.1	47.7
4	24.8	30.5	33.5	36.4	39.9	40.9	42.2
5	24.0	28.4	31.1	33.4	36.2	37.3	38.4
6	23.4	26.5	29.1	31.1	33.5	34.5	35.6
7	22.9	25.1	27.4	29.3	31.3	32.4	33.3
8	22.4	23.8	25.9	27.6	29.4	30.4	31.3
9	22.2	22.8	24.7	26.3	27.8	28.7	29.6
10	21.9	22.1	23.7	25.2	26.5	27.4	28.2
11	21.6	21.5	22.8	24.3	25.4	26.3	27.0
12	21.4	20.9	22.1	23.3	24.5	25.2	25.9
13	21.3	20.6	21.5	22.7	23.7	24.3	24.9
14	21.3	20.3	21.2	22.2	23.0	23.6	24.3
15	20.9	20.1	20.6	21.6	22.3	22.9	23.4

Initial moisture content = 18.1 %DB

Pellet diameter = 4.76 mm, Pellet density = 945 Kg/m³

Pellet bulk density = 673 Kg/m³, Bed depth = 30.48 cm

Table A.13 - Experimental Values of Moisture Content (%DB) within a Fixed-Bed of Pellets Cooled at Two Airflow rates. Air Temperature 21.1 C, RH 55%. Tests 1 and 2.

Cooler Depth (cm)	Air Velocity = .5 m/s		.1 m/s	
	Cooling Time (min)		Time (min)	
	10	15	20	15
Bottom	18.5	18.3	17.8	18.2
10.16	17.4	17.4	17.0	17.6
20.32	17.2	17.1	17.0	17.9
30.48	16.3	17.2	16.9	17.8
Average	17.6	17.5	17.2	17.9

Initial moisture content = 20.7 %DB

Table A.14 - Experimental Values of Moisture Content (%DB) within a Fixed-Bed of Pellets Cooled at Two Airflow rates. Air Temperature 32.2 C, RH 55%. Tests 5 and 6.

Cooler Depth (cm)	Air Velocity = .5 m/s			.1 m/s	
	Cooling Time (min)			Time (min)	
	10	15	20	15	20
Bottom	16.2	15.9	15.4	16.2	15.8
10.16	16.3	16.0	15.8	16.4	16.0
20.32	16.3	16.1	15.9	16.7	16.0
30.48	16.3	16.1	16.0	17.1	16.2
Average	16.3	16.0	15.8	16.6	16.0

Initial moisture content = 19.1 %DB

Table A.15 - Experimental Values of Moisture Content (%DB) within a Fixed-Bed of Pellets Cooled at Two Airflow rates. Air Temperature 17.7 C, RH 70%. Tests 7 and 8.

Cooler Depth (cm)	Air Velocity = .5 m/s		.1 m/s	
	Cooling Time (min)		Time (min)	
	10	15	20	20
Bottom	18.6	18.1	17.4	18.0
10.16	17.5	17.1	16.9	17.5
20.32	16.8	16.4	16.1	17.2
30.48	16.8	16.6	15.9	17.4
Average	17.4	17.0	16.6	17.5

Initial moisture content = 19.6 %DB

Table A.16 - Experimental Values of Moisture Content (%DB) within a Fixed-Bed of Pellets Cooled at Two Airflow rates. Air Temperature 21.1 C, RH 70%. Tests 9 and 10.

Cooler Depth (cm)	Air Velocity = .5 m/s			.1 m/s	
	Cooling Time (min)				
	10	15	20	15	20
Bottom	19.0	18.9	18.9	18.7	18.7
10.16	17.8	18.0	17.9	17.7	17.5
20.32	17.3	17.2	17.2	17.6	17.2
30.48	17.1	16.9	16.9	18.1	17.3
Average	17.8	17.8	17.7	18.0	17.7

Initial moisture content = 19.8 %DB

Table A.17 - Experimental Values of Moisture Content (%DB) within a Fixed-Bed of Pellets Cooled at Two Airflow rates. Air Temperature 26.7 C, RH 70%. Tests 11 and 12.

Cooler Depth (cm)	Air Velocity = .5 m/s			.1 m/s	
	Cooling Time (min)				
	10	15	20	15	
Bottom	18.9	19.1	19.2	18.8	
10.16	18.0	17.7	17.7	18.0	
20.32	17.8	17.6	17.5	17.9	
30.48	17.6	17.4	17.3	18.3	
Average	18.1	17.9	17.9	18.3	

Initial moisture content = 20.5 %DB

Table A.18 - Experimental Values of Moisture Content (%DB) within a Fixed-Bed of Pellets Cooled at Two Airflow rates. Air Temperature 21.1 C, RH 55%. Tests 13 and 14.

Cooler Depth (cm)	Air Velocity = .1 m/s			.5 m/s	
	Cooling Time (min)				
	10	15	20	15	
Bottom	16.0	15.7	15.6	15.9	
10.16	15.2	15.1	14.8	15.1	
20.32	15.6	15.2	14.9	15.0	
30.48	15.9	15.7	15.3	15.4	
Average	15.7	15.4	15.2	15.4	

Initial moisture content = 18.1 %DB

APPENDIX B

PSYCHROMETRIC CHART MODEL AND SAMPLE OUTPUT

PSYCHROMETRIC CHART MODEL

```

100 CLS
102 REM PSYCHROMETRIC CHART MODEL
104 REM
106 REM JOAD D. BIAGI - SPRING/86 - MSU - E.LANSING
108 REM
110 PRINT TAB(5) " " STRING$(59,"*")
112 LOCATE 2,12
114 PRINT "FROM TWO GIVEN INDEPENDENT PROPERTIES OF THE MOIST AIR THIS"
116 LOCATE 3,12
118 PRINT "PSYCHROMETRIC CHART MODEL COMPUTES THE REMAINING PROPERTIES"
120 LOCATE 4,12
122 PRINT "OF A STATE POINT. THE INPUTS MAY BE IN ENGLISH OR SI UNITS."
124 PRINT TAB(5) " " STRING$(59,"*")
126 PRINT: PRINT
128 PRINT SPC(18) " YOU HAVE SEVEN CHOICES FOR INPUTS: "
130 PRINT:PRINT
132 PRINT SPC(18) " 1) DRY BULB TEMP. AND RELATIVE HUMIDITY "
134 PRINT SPC(18) " 2) DRY BULB TEMP. AND ABSOLUTE HUMIDITY "
136 PRINT SPC(18) " 3) DRY BULB TEMP. AND WET BULB TEMP. "
138 PRINT SPC(18) " 4) DRY BULB TEMP. AND DEW POINT TEMP."
140 PRINT SPC(18) " 5) WET BULB TEMP. AND RELATIVE HUMIDITY "
142 PRINT SPC(18) " 6) DEW POINT TEMP. AND RELATIVE HUMIDITY "
144 PRINT SPC(18) " 7) DEW POINT TEMP. AND ENTHALPY "
146 LOCATE 19,23: INPUT " ENTER A NUMBER FROM 1 TO 7 " = " , I
148 IF (I>=1) AND (I<=7) GOTO 150 ELSE LOCATE 8,1: GOTO 128
150 LOCATE 21,25:INPUT "ENGLISH OR SI UNITS ( E or SI ) ? " ,U$
152 IF (U$="E") OR (U$="e") GOTO 156
154 IF (U$="SI") OR (U$="si") GOTO 160 ELSE GOTO 150
156 T$="( F )":AB$=" (LB H2O/LB DRY AIR) ":E$=" (BTU/LB DRY AIR) "
158 GOTO 162
160 T$="( C )":AB$=" (KG H2O/KG DRY AIR) ":E$=" (KJ/KG DRY AIR) "
162 LOCATE 23,8
164 IF I=1 GOTO 170 ELSE IF I=2 GOTO 174 ELSE IF I=3 GOTO 178
166 IF I=4 GOTO 184 ELSE IF I=5 GOTO 190 ELSE IF I=6 GOTO 194
168 IF I=7 GOTO 198
170 PRINT "DRY BULB TEMP. "T$","RELATIVE HUMIDITY (%) ";;INPUT DB,RH
172 IF RH>100 THEN PRINT " RH > 100 ":GOTO 170:ELSE GOTO 200
174 PRINT "DRY BULB TEMP."T$","ABS. HUMIDITY "AB$;;INPUT DB,HA
176 GOTO 200
178 PRINT "DRY BULB TEMP. "T$","WET BULB TEMP. "T$" ";;INPUT DB,WB
180 IF DB < WB THEN PRINT " DB < WB ": GOTO 178
182 GOTO 200
184 PRINT "DRY BULB TEMP. "T$","DEW POINT TEMP. "T$" ";;INPUT DB,DP
186 IF DB < DP THEN PRINT " DB < DP ": GOTO 184
188 GOTO 200

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190 PRINT "WET BULB TEMP. "T$","RELATIVE HUMIDITY (%) ";:INPUT WB,RHI
192 IF RHI>100 THEN PRINT " RH > 100 ":GOTO 190:ELSE GOTO 200
194 PRINT "DEW POINT TEMP."T$","RELATIVE HUMIDITY (%) ";:INPUT DP,RH
196 IF RH>100 THEN PRINT " RH > 100 ":GOTO 194:ELSE GOTO 200
198 PRINT "DEW POINT TEMP."T$","ENTHALPY "E$";:INPUT DP,H
200 RH = RH / 100: RHI = RHI / 100
202 IF (U$="E") OR (U$="e") GOTO 206
204 DB=DB+1.8+32: WB=WB+1.8+32: DP=DP+1.8+32: H=H/2.326
206 REM PRINT FORMATS
208 F1$=" #####.## ":F2$=" ###.##### ":F3$="#####.#### "
210 F4$="#####.### ":F5$=" #####.### "
212 P$=" LB/SQ IN ":AH$=" LB M/LB D.AIR ":EN$=" BTU/LB D.AIR "
214 VS$=" FT3/LB D.AIR ":AH1$=" KGM/KG D.AIR":EN1$=" KJ/KG D.AIR"
216 VSI$=" M3/KG D.AIR": PI$=" KPa"
218 REM MAIN PROGRAM
220 IF I = 5 GOTO 260 ELSE IF (I=6) OR (I=7) GOTO 236
222 T = DB + 459.69: GOSUB 496
224 PSD = PS: IF I=7 THEN RH = PDP/PSD: GOTO 254
226 IF I=4 THEN T=DP+459.69:GOSUB 496:PDP=PS:RH=PDP/PSD:PV=PS:GOTO 254
228 IF I = 3 GOTO 260
230 IF I=2 THEN PV=HA*14.696/((.6219+HA):RH=PV/PSD:GOTO 234
232 PV=PSD * RH:IF I=5 THEN PV = PSD * RHI
234 GOSUB 526: DP = A * PV^B + C*LOG(PV) + D
236 T = DP + 459.69: GOSUB 496
238 PDP = PS: IF I=7 THEN PV=PDP: GOTO 290
240 IF I< >6 GOTO 252 ELSE PSD=PDP/RH:PV=PDP
242 DELT = 10: DB = DP
244 T = DB+459.69: GOSUB 496: PSDA = PS
246 XP=PSD-PSDA:IF XP>0 THEN DB=DB+DELT:GOTO 244
248 IF (DELT<.00001) OR (XP=0) GOTO 252
250 IF XP<0 THEN DB=DB-DELT:DELT=DELT/2:DB=DB+DELT:GOTO 244
252 IF I = 3 GOTO 294 ELSE IF I = 5 GOTO 290
254 DT = DB - DP
256 GOSUB 544
258 WB=DP+(B1*DT^3+B2*DT^2+B3*DT)*EXP((B4*DT+B5)*DP^B6)
260 T = WB + 459.69: GOSUB 496
262 PWB = PS
264 IF I = 7 GOTO 294
266 IF I < > 5 GOTO 278
268 DELT = 10: DB = WB
270 T=DB+459.69:GOSUB 496:PSD=PS:T=DB:GOSUB 508:GOTO 284
272 XP=RHA-RHI:IF XP>0 THEN DB=DB+DELT:GOTO 270
274 IF (DELT<.00001) OR (XP=0) GOTO 232
276 IF XP<0 THEN DB=DB-DELT:DELT=DELT/2:DB=DB+DELT:GOTO 270
278 IF I = 4 GOTO 290
280 IF I < > 3 GOTO 288
282 T=WB: GOSUB 508
284 BP=.2405 * (PWB-14.696)/(.62194*HF6)
286 PV=PWB+BP*(DB-WB):RH=PV/PSD:IF I=5 THEN RHA=RH:GOTO 272
288 IF I=2 GOTO 294
290 HA=.62198 * (PV/(14.696-PV))
292 IF I=3 GOTO 234 ELSE IF I=7 GOTO 308
294 SV=(53.35*(DB+459.69))/(144*(14.696-PV))
296 IF I=7 GOTO 318
298 IF DP>32 GOTO 304

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300 H=.2405*DB+HA*(.448*(DB+459.69)-.01377*(DP+459.69)+862.3629)
302 GOTO 318
304 H=.2405*DB+HA*(.448*(DB+459.69)-.01783*(DP+459.69)+864.7168)
306 GOTO 318
308 IF DP>= 32 GOTO 314
310 DB=(H-HA*(1068.30402#-.01377*(DP+459.69)))/(.2405+HA*.448)
312 GOTO 222
314 DB=(H-HA*(1070.65792#-.01783*(DP+459.69)))/(.2405+HA*.448)
316 GOTO 222
318 REM TRANSFORMS ENGLISH UNITS TO SI UNITS
320 DBI=(DB-32)/1.8;WBI=(WB-32)/1.8;DPI=(DP-32)/1.8
322 RH=RH*100;IF I=5 THEN RH=RHI*100
324 PSDI=PSD*6.894757;PWBI=PWB*6.894757;PDPI=PDP*6.894757
326 SVI = SV * .062428; HI = H * 2.326
328 CLS;PRINT;PRINT SPC(19);
330 PRINT "RESULTS FROM THE PSYCHROMETRIC CHART MODEL"
332 PRINT SPC(19) "INPUTS = ";
334 IF I = 1 THEN PRINT " DRY BULB TEMP. AND RELATIVE HUMIDITY"
336 IF I = 2 THEN PRINT " DRY BULB TEMP. AND ABSOLUTE HUMIDITY"
338 IF I = 3 THEN PRINT " DRY BULB TEMP. AND WET BULB TEMP."
340 IF I = 4 THEN PRINT " DRY BULB TEMP. AND DEW POINT TEMP."
342 IF I = 5 THEN PRINT " WET BULB TEMP. AND RELATIVE HUMIDITY"
344 IF I = 6 THEN PRINT "DEW POINT TEMP. AND RELATIVE HUMIDITY"
346 IF I = 7 THEN PRINT " DEW POINT TEMP. AND ENTHALPY "
348 PRINT; PRINT
350 PRINT SPC(25) " ENGLISH UNITS " SPC(18) " SI UNITS "
352 PRINT
354 PRINT SPC(3) " DRY BULB TEMP. ";PRINT USING F1$;DB;
356 PRINT " F";PRINT SPC(18) USING F1$;DBI;PRINT " C"
358 PRINT SPC(3) " WET BULB TEMP. ";PRINT USING F1$;WB;
360 PRINT " F";PRINT SPC(18) USING F1$;WBI;PRINT " C"
362 PRINT SPC(3) " DEW POINT TEMP. ";PRINT USING F1$;DP;
364 PRINT " F";PRINT SPC(18) USING F1$;DPI;PRINT " C"
366 PRINT SPC(3) " RELATIVE HUMIDITY ";PRINT USING F1$;RH;
368 PRINT " %";PRINT SPC(18) USING F1$;RH;PRINT " %"
370 PRINT SPC(3) " ABSOLUTE HUMIDITY ";PRINT USING F2$; HA;
372 PRINT AH$;PRINT SPC(5) USING F2$;HA;PRINT AH1$
374 PRINT SPC(3) " ENTHALPY ";PRINT USING F4$;H;
376 PRINT EN$;PRINT SPC(7) USING F4$;HI;PRINT EN1$
378 PRINT SPC(3) " AIR SPECIFIC VOL. ";PRINT USING F1$;SV;
380 PRINT VS$;PRINT SPC(6) USING F5$;SVI;PRINT VSI$
382 PRINT
384 PRINT SPC(3) " SATURATION VAPOR PRESSURES "
386 PRINT
388 PRINT SPC(4) " AT DRY BULB TEMP. ";PRINT USING F3$;PSD;
390 PRINT P$;PRINT SPC(11) USING F3$;PSDI;PRINT PI$
392 PRINT SPC(4) " AT WET BULB TEMP. ";PRINT USING F3$;PWB;
394 PRINT P$;PRINT SPC(11) USING F3$;PWBI;PRINT PI$
396 PRINT SPC(4) " AT DEW POINT TEMP.";PRINT USING F3$;PDP;
398 PRINT P$;PRINT SPC(11) USING F3$;PDPI;PRINT PI$
400 REM
402 LOCATE 22,2
404 INPUT "DO YOU WANT THE RESULTS PRINTED OUT? (Y or N) ",PR$
406 IF PR$="N" OR PR$="n" GOTO 484
408 IF PR$="Y" OR PR$="y" GOTO 410 ELSE GOTO 402

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410 LPRINT;LPRINT:LPRINT SPC(19);
412 LPRINT "RESULTS FROM THE PSYCHROMETRIC CHART MODEL"
414 LPRINT SPC(19) "INPUTS = ";
416 IF I = 1 THEN LPRINT " DRY BULB TEMP. AND RELATIVE HUMIDITY"
418 IF I = 2 THEN LPRINT " DRY BULB TEMP. AND ABSOLUTE HUMIDITY"
420 IF I = 3 THEN LPRINT " DRY BULB TEMP. AND WET BULB TEMP."
422 IF I = 4 THEN LPRINT " DRY BULB TEMP. AND DEW POINT TEMP."
424 IF I = 5 THEN LPRINT " WET BULB TEMP. AND RELATIVE HUMIDITY"
426 IF I = 6 THEN LPRINT "DEW POINT TEMP. AND RELATIVE HUMIDITY"
428 IF I = 7 THEN LPRINT " DEW POINT TEMP. AND ENTHALPY "
430 LPRINT; LPRINT
432 LPRINT SPC(25) " ENGLISH UNITS " SPC(18) " SI UNITS "
434 LPRINT; LPRINT
436 LPRINT SPC(3) " DRY BULB TEMP. ";LPRINT USING F1$;DB;
438 LPRINT " F";LPRINT SPC(18) USING F1$;DBI;LPRINT " C"
440 LPRINT SPC(3) " WET BULB TEMP. ";LPRINT USING F1$;WB;
442 LPRINT " F";LPRINT SPC(18) USING F1$;WBI;LPRINT " C"
444 LPRINT SPC(3) " DEW POINT TEMP. ";LPRINT USING F1$;DP;
446 LPRINT " F";LPRINT SPC(18) USING F1$;DPI;LPRINT " C"
448 LPRINT SPC(3) " RELATIVE HUMIDITY ";LPRINT USING F1$;RH;
450 LPRINT " %";LPRINT SPC(18) USING F1$;RH;LPRINT " %"
452 LPRINT SPC(3) " ABSOLUTE HUMIDITY ";LPRINT USING F2$;HA;
454 LPRINT AH$;LPRINT SPC(5) USING F2$;HA;LPRINT AH$
456 LPRINT SPC(3) " ENTHALPY ";LPRINT USING F4$;H;
458 LPRINT EN$;LPRINT SPC(7) USING F4$;HI;LPRINT EN$
460 LPRINT SPC(3) " AIR SPECIFIC VOL. ";LPRINT USING F1$;SV;
462 LPRINT VS$;LPRINT SPC(6) USING F1$;SVI;LPRINT VSI$
464 LPRINT
466 LPRINT SPC(3) " SATURATION VAPOR PRESSURES "
468 LPRINT
470 LPRINT SPC(4) " AT DRY BULB TEMP. ";LPRINT USING F3$;PSD;
472 LPRINT P$;LPRINT SPC(11) USING F4$;PSDI;LPRINT PI$
474 LPRINT SPC(4) " AT WET BULB TEMP. ";LPRINT USING F3$;PWB;
476 LPRINT P$;LPRINT SPC(11) USING F3$;PWBI;LPRINT PI$
478 LPRINT SPC(4) " AT DEW POINT TEMP.";LPRINT USING F3$;PDP;
480 LPRINT P$;LPRINT SPC(11) USING F3$;PDPI;LPRINT PI$
482 REM
484 LOCATE 23,2
486 INPUT "DO YOU WANT TO INPUT NEW DATA? (Y or N) ",ND$
488 IF ND$="N" OR ND$="n" GOTO 492
490 IF ND$="Y" OR ND$="y" GOTO 100 ELSE GOTO 484
492 END
494 REM
496 REM SUBROUTINE SATURATION VAPOR PRESSURE
498 IF T > 491.69 GOTO 504
500 PS=EXP(23.3924#-(11286.6489#/T)-.46057*L06(T))
502 GOTO 506
504 PS=EXP(54.6329#-(12301.688#/T)-5.16923#*L06(T))
506 RETURN
508 REM SUBROUTINE LATENT HEAT OF VAPORIZATION
510 IF (T>32) AND (T<150) THEN GOTO 518
512 IF T>150 GOTO 522
514 HFG=1220.844#-.05077#*T
516 GOTO 524
518 HFG=1075.8965#-.56983*(T-32)

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520 GOTO 524
522 HF6=(1354673.214#-.912527558#*(T+459.69)^2)^.5
524 RETURN
526 REM SUBROUTINE CONSTANTS OF DEW POINT TEMP. EQUATION
528 IF (PS>.0886) AND (PS<14.696) GOTO 536
530 IF PS>14.696 GOTO 540
532 A=18.44049#;B=.1171117#;C=.5561646#;D=-.9335884#
534 GOTO 542
536 A=92.29778#;B=.2226883#;C=12.88743#;D=9.415002#
538 GOTO 542
540 A=44.11702#;B=.2949225#;C=21.77737#;D=55.98703#
542 RETURN
544 REM SUBROUTINE CONSTANTS OF WET BULB TEMP. EQUATION
546 IF DP >= 32 GOTO 580
548 DBA=-1.1756E-04*DP^3-.0032646*DP^2-.19195*DP+45.35
550 IF (DB>=DBA) AND (DB<180) THEN GOTO 562
552 IF (DB>180) AND (DB<300) THEN GOTO 568
554 IF DB > 300 GOTO 574
556 B1=9.04803E-07;B2=-.0033017;B3=.831231;B4=-2.3949E-05
558 B5=-8.08793E-03;B6=1.130519
560 GOTO 600
562 B1=5.54717E-06;B2=-3.14334E-03;B3=.84224;B4=5.93269E-06
564 B5=-8.630321E-03;B6=1.082753
566 GOTO 600
568 B1=2.32489E-06;B2=-2.04027E-03;B3=.746559;B4=6.24943E-06
570 B5=8834.849;B6=1.074474
572 GOTO 600
574 B1=8.64159E-07;B2=-.0011678;B3=.615543;B4=.392047
576 B5=-.0082495;B6=1.070437
578 GOTO 600
580 IF (DB>180) AND (DB<300) THEN GOTO 590
582 IF DB > 300 THEN GOTO 596
584 B1=7.37013E-06;B2=-3.53885E-03;B3=.827522;B4=3.89627E-06
586 B5=-2.60113E-03;B6=1.404192
588 GOTO 600
590 B1=2.49546E-06;B2=-2.04326E-03;B3=.707415;B4=1.88247E-06
592 B5=-2.00086E-03;B6=1.442215
594 GOTO 600
596 B1=8.44289E-07;B2=-1.10977E-03;B3=.572561;B4=8.97368E-07
598 B5=-1.53339E-03;B6=1.475598
600 RETURN

```

RESULTS FROM THE PSYCHROMETRIC CHART MODEL
 INPUTS = DRY BULB TEMP. AND RELATIVE HUMIDITY

ENGLISH UNITS			SI UNITS	
DRY BULB TEMP.	75.00	F	23.89	C
WET BULB TEMP.	67.93	F	19.96	C
DEW POINT TEMP.	64.54	F	18.08	C
RELATIVE HUMIDITY	70.00	%	70.00	%
ABSOLUTE HUMIDITY	0.01298	LB M/LB D.AIR	0.01298	KG M/KG D.AIR
ENTHALPY	32.252	BTU/LB D.AIR	75.018	KJ/KG D.AIR
AIR SPECIFIC VOL.	13.76	FT ³ /LB D.AIR	0.86	M ³ /KG D.AIR
SATURATION VAPOR PRESSURES				
AT DRY BULB TEMP.	0.4292	LB/SQ IN	2.960	KPa
AT WET BULB TEMP.	0.3379	LB/SQ IN	2.3296	KPa
AT DEW POINT TEMP.	0.3003	LB/SQ IN	2.0708	KPa

RESULTS FROM THE PSYCHROMETRIC CHART MODEL
 INPUTS = WET BULB TEMP. AND RELATIVE HUMIDITY

ENGLISH UNITS			SI UNITS	
DRY BULB TEMP.	77.29	F	25.16	C
WET BULB TEMP.	70.00	F	21.11	C
DEW POINT TEMP.	66.72	F	19.29	C
RELATIVE HUMIDITY	70.00	%	70.00	%
ABSOLUTE HUMIDITY	0.01403	LB M/LB D.AIR	0.01403	KG M/KG D.AIR
ENTHALPY	33.963	BTU/LB D.AIR	78.997	KJ/KG D.AIR
AIR SPECIFIC VOL.	13.84	FT ³ /LB D.AIR	0.86	M ³ /KG D.AIR
SATURATION VAPOR PRESSURES				
AT DRY BULB TEMP.	0.4631	LB/SQ IN	3.193	KPa
AT WET BULB TEMP.	0.3626	LB/SQ IN	2.5003	KPa
AT DEW POINT TEMP.	0.3240	LB/SQ IN	2.2339	KPa

APPENDIX C

HEAT AND MASS BALANCE MODEL AND SAMPLE OUTPUT

HEAT AND MASS BALANCE MODEL
FOR STATIONARY-BED PELLET COOLER

```

100 CLS
102 REM MODEL #1 - HEAT AND MASS BALANCE (HMB)
104 REM COOLING OF A FIXED BED OF PELLETS
106 REM PROGRAM: PELLET1
108 REM
110 REM THIS PROGRAM COMPUTES PELLET MOISTURE CONTENTS AND TEMPERATURES,
112 REM ABSOLUTE AND RELATIVE HUMIDITIES WITHIN A FIXED BED OF PELLETS.
114 REM BASED ON THOMPSON (1967) APPROACH. AIR AND PELLET TEMPERATURES
116 REM ARE ASSUMED TO BE EQUAL.
118 REM
120 REM JOAO BIAGI - SUMMER/86 - MSU - EAST LANSING
122 REM
124 DIM H(361),RH(361),EMCD(361),TPT(361,2),TA(361)
126 DIM LA(5),AA(5),B(5),AR(5),MC(361,2)
128 REM INPUT BLOCK
130 CLS:LOCATE 3,10:PRINT " INPUT VALUES":PRINT
132 INPUT " Air Temperature (F) " = ", TAI
134 INPUT " Relative Humidity (%) " = ", RHI
136 INPUT " Air Flow Rate (CFM/FT2) " = ", CFM
138 INPUT " Pellet Temperature (F) " = ", TPI
140 INPUT " Initial Moisture Content (%WB) " = ", MCIW
142 INPUT " Pellet Diameter (In.) " = ", DIAI
144 INPUT " Cooling Time (Min) " = ", TI
146 PRINT
148 REM DIAMETER IN FOOT and RADIUS IN METER
150 DIAI=.1875:DIAF=DIAI/12:R=(DIAI/2)*.0254
152 REM COOLER DEPTH (FT); AREA (FT2)
154 BED=1:AREA=1
156 REM CONSTANTS OF MOIST. CONTENT EQN..ROOTS BESSEL FC.
158 KL=3:FOR I=1 TO KL: READ LA(I)
160 AA(I)=LA(I)*LA(I):B(I)=4/AA(I):AR(I)=-AA(I)/(R*R):NEXT I
162 DATA 2.405,5.52,8.654
164 REM COOLING TIME (HOUR)
166 TI=TI/60
168 REM PELLET DENSITY (LB/FT3); (KG/M3)
170 PDEE=42:PDEM=PDEE+16.0185
172 RHC = .98
174 REM DT=HOUR; TC=# OF ITERATIONS
176 DT=1/60: TC=TI/DT
178 REM
180 REM RH=DECIMAL;MC=DECIMAL DRY BASIS
182 RHI=RHI/100:MCID=MCIW/(100-MCIW)
184 REM COMPUTE INLET ABS.HUMIDITY AND SPEC.VOLUME
186 IJ=1:DB=TAI:RH=RHI:GOSUB 358:HI=HU:SVI=SV
188 REM COMPUTE AIR FLOW (LB/Hr)
190 GA=(CFM*60)/(AREA*SVI)
192 REM COMPUTE DEPTH INCREMENT

```

```

194 IF CFM<=30 THEN XA=760 ELSE XA=510
196 XT=INT(XA*(CFM/AREA)^-.5028)
198 XPR=XT/6
200 IF (INT(XPR)-XPR)<0 THEN XT=XT-1:GOTO 198
202 DELX=1/XT
204 REM AIR VELOCITY (M/S)
206 VA=(CFM*.3048)/60
208 C1 = PDEE*DELX/(GA*DT)
210 F1$=" ###.##":F2$=" .####":F3$=" ##.## "
212 REM PRINT INITIAL CONDITIONS
214 CLS: LOCATE 5,2: GOSUB 422: GOSUB 516
216 REM INITIALIZE ARRAY POSITIONS
218 DK=459.69
220 TA(0)=TAI+DK:RH(0)=RHI:TPI=TPI+DK:TAI=TAI+DK
222 TPT(0,0)=(TAI+TPI)/2: ST=0:SM=0
224 FOR X = 0 TO XT:TPT(X+1,0)=TPI:H(X)=HI:MC(X,0)=MCID
226 TA(X+1)=TPI: ST=ST+TPT(X,0): SM=SM+MC(X,0)
228 NEXT X
230 TPA=((ST/X)-491.69)/1.8:MCAVE=SM/X
232 REM
234 L=0:GOSUB 466: GOSUB 570
236 REM
238 CPRI=0:PTI=1/(DT*60)
240 REM TIME LOOP
242 FOR N=1 TO TC:L=N/60
244 CPRI=CPRI+1:SMC=0:STA=0
246 LOCATE 22,5
248 PRINT " ELAPSED TIME = ";PRINT USING "##.##"; L*60;
250 PRINT " min.:";PRINT " COMPUTING CONDITIONS AT "
252 REM DEPTH LOOP
254 FOR X = 0 TO XT
256 LOCATE 22,56
258 PRINT USING " ##.##";((X*30.48*BED)/XT);PRINT " cm."
260 REM EQUILIBRIUM MOISTURE CONTENT EQUATIONS
262 TPC=(TPT(X,0)-491.69)/1.8
264 REM NELLIST EQUATION
266 REM EMCD(X)=.191-.055*LOG(1-RH(X))-.028*LOG(TPC)
268 REM HENDERSON EQUATION
270 REM EMCD(X)=(-LOG(1-RH(X)))/(6.66*(TPC+22.12)))^(1/3.11)
272 REM CHUNG-PFOST EQUATION
274 EMCD(X)=.277-.042*LOG(-(TPC+13.3)*LOG(RH(X)))
276 REM DIFFUSION COEFFICIENT EQUATION
278 DIC=1.015E-05*EXP(-547/(TPC+273.15))
280 REM MOISTURE CONTENT DIFFUSION EQN.
282 SUMM=0:FOR I = 1 TO KL
284 SUMC=B(I)*EXP(AR(I)*DIC*L)
286 SUMM=SUMM+SUMC:NEXT I
288 MC(X,1)=EMCD(X)+(MCID-EMCD(X))*SUMM
290 REM ABSOLUTE HUMIDITY EQUATION
292 H(X+1)=H(X)-C1*(MC(X,1)-MC(X,0))
294 DH=H(X+1)-H(X)
296 REM EQUILIBRIUM TEMPERATURE EQUATION
298 CP=4.18*(.343+MC(X,0))/(1+MC(X,0))
300 T1=1.005+2467.4*H(X):T2=CP*TPT(X,0):T3=T1+TA(X)
302 TA(X+1) = (T3+T2)/(T1+CP)

```

```

304 REM LATENT HEAT EQUATIONS
306 HFGA=1094-.57*(TA(X)-459.69)
308 HFG=HFGA*(1+4.349*EXP(-28.25*MC(X,0)))
310 REM PELLET TEMPERATURE EQUATION
312 DHFG=(HFG-HFGA)*2.326
314 TP1=(1.005+1.884*H(X))*TA(X)
316 TP2=DH*(2740.56+DHFG-TPT(X,0))
318 TP3=CP*((TA(X)+TPT(X,0))/2):TP4=1.005+1.884*H(X+1)
320 TPT(X,1) = (TP1-TP2+TP3)/(TP4+CP)
322 SMC=SMC+MC(X,1):STA=STA+TPT(X,1)
324 REM RELATIVE HUMIDITY
326 IJ=2:DB=TA(X+1)-459.69:HU=H(X+1):GOSUB 358:RH(X+1)=RH
328 IF RH>RHC THEN RH(X+1)=RHC
330 NEXT X
332 MCAVE=SMC/X:TPA=((STA/X)-491.69)/1.8
334 FOR X=0 TO XT:MC(X,0)=MC(X,1):TPT(X,0)=TPT(X,1):NEXT X
336 REM
338 GOSUB 466
340 IF PTI=CPRI THEN CPRI=0:GOSUB 570
342 NEXT N
344 REM
346 LOCATE 23,5
348 INPUT " DO YOU WANT TO INPUT NEW DATA? (Y or N) ",ND$
350 IF ND$="N" OR ND$="n" GOTO 354
352 IF ND$="Y" OR ND$="y" GOTO 130 ELSE GOTO 346
354 END
356 REM
358 REM SUBROUTINE PSYCHART(DB,WB,DP,RH,HU,PV,SV,HFG)
360 IF DB > 212 GOTO 366
362 A#=92.29778#:B#=.2226883#:C#=12.88743#:D#=9.415002#
364 GOTO 368
366 A#=44.11702#:B#=.2949225#:C#=21.77737#:D#=55.98703#
368 IF DB > 180 GOTO 376
370 B1#=-7.37013E-06:B2#=-3.53885E-03:B3#=.827522#:B4#=3.89627E-06
372 B5#=-2.60113E-06:B6#=1.404191#
374 GOTO 380
376 B1#=-2.49546E-06:B2#=-2.04326E-03:B3#=.707415#:B4#=1.88247E-06
378 B5#=-2.00086E-03:B6#=1.442215#
380 T=DB+459.69
382 PS=EXP(54.6329#-(12301.688#/T)-5.16923#*LOG(T))
384 IF IJ=2 THEN PV=HU*14.696/(.621+HU):RH=PV/PS:GOTO 388
386 PV=PS*RH
388 DP=A#*PV^B#+C#*LOG(PV)+D#
390 DTD=DB-DP
392 WB=DP+(B1#*DTD^3+B2#*DTD^2+B3#*DTD)*EXP((B4#*DTD+B5#)*DP^B6#)
394 IF IJ = 2 GOTO 398
396 HU=.6219*(PV/(14.696-PV))
398 SV=(53.35#*(DB+459.69))/(144*(14.696-PV))
400 GOTO 416
402 T=DB
404 IF (T>32) AND (T<150) THEN GOTO 410 ELSE IF T>150 GOTO 414
406 HFG=1220.844#-.05077#*T
408 GOTO 416
410 HFG=1075.8965#-.56983#*(T-32)
412 GOTO 416

```

```

414 HF8=(1354673.2148-.91252755878*(T+459.69)^2)^.5
416 RETURN
418 REM SUBROUTINES PRINT = SCREEN
420 REM
422 PRINT:PRINT
424 PRINT TAB(10) " INITIAL CONDITIONS ": PRINT
426 PRINT TAB(5) " AIR TEMPERATURE (F) = ";
428 PRINT USING F1$;TAI,(TAI-32)/1.8;PRINT " C"
430 PRINT TAB(5) " RELATIVE HUMIDITY (%) = ";
432 PRINT USING F1$;RHI*100
434 PRINT TAB(6) "PELLET TEMPERATURE (F) = ";PRINT USING F1$;TPI;
436 PRINT USING F1$;(TPI-32)/1.8;PRINT " C"
438 PRINT TAB(6) "MOISTURE CONTENT (% WB) = ";PRINT USING F1$;MCIW;
440 PRINT USING F1$;MCID*100;PRINT " %DB"
442 PRINT TAB(5) " PELLET DIAMETER (In.) = ";
444 PRINT USING F2$;DIAI;PRINT USING F1$;DIAI*25.4;PRINT " MM"
446 PRINT TAB(6) "AIR FLOW (CFM/FT2) = ";PRINT USING F1$;CFM;
448 PRINT USING F1$;VA;PRINT " M/S"
450 PRINT TAB(5) " COOLER DEPTH (FT) = ";
452 PRINT USING F1$;BED,BED*30.48;PRINT " CM"
454 PRINT TAB(6) "DELTA X (In.) = ";PRINT USING F1$;DELX*12;
456 PRINT USING F1$;DELX*30.48;PRINT " CM"
458 PRINT TAB(6) "DELTA t (Min.) = ";PRINT USING F1$;DT*60
460 PRINT
462 RETURN
464 REM
466 CLS:LOCATE 1,2:PRINT
468 PRINT TAB(6) "TIME (Min.) = ";PRINT USING F3$;L*60
470 PRINT:PRINT TAB(5) " BED DEPTH cm";
472 FOR Y=0 TO (12*BED) STEP (2*BED):PRINT USING F1$;Y*2.54;
474 NEXT Y:PRINT:PRINT:PRINT TAB(5) " EQ. TEMP. C ";
476 KT=491.69
478 FOR Y=0 TO XT STEP XPR:PRINT USING F1$;(TA(Y)-KT)/1.8;NEXT Y
480 PRINT:PRINT TAB(5) " PEL.TEMP. C ";
482 FOR Y=0 TO XT STEP XPR:PRINT USING F1$;(TPT(Y,0)-KT)/1.8;
484 NEXT Y:PRINT:PRINT TAB(5) " M.C. %DB ";
486 FOR Y=0 TO XT STEP XPR:PRINT USING F1$;MC(Y,0)*100;NEXT Y
488 PRINT TAB(5) " M.C. %WB ";FOR Y=0 TO XT STEP XPR
490 W=MC(Y,0):PRINT USING F1$;(W/(1+W))*100;NEXT Y
492 IF L = 0 GOTO 504
494 PRINT:PRINT TAB(5) " EQ.MC. %DB ";
496 FOR Y=0 TO XT STEP XPR:PRINT USING F1$;EMCD(Y)*100;NEXT Y
498 PRINT:PRINT TAB(5) " REL. HUMID. ";
500 FOR Y=0 TO XT STEP XPR:PRINT USING F1$;RH(Y)*100;NEXT Y
502 PRINT
504 PRINT TAB(5) " ABS. HUMID. ";
506 FOR Y=0 TO XT STEP XPR:PRINT USING F2$;H(Y);NEXT Y:PRINT
508 PRINT:PRINT TAB(11) "AVE. TEMP. (C) = ";PRINT USING F1$;TPA;
510 PRINT " AVE. MC. (%DB) = ";PRINT USING F1$;MCAVE*100
512 RETURN
514 REM SUBROUTINES PRINT = PRINTER
516 LPRINT
518 LPRINT TAB(10) " INITIAL CONDITIONS ":LPRINT
520 LPRINT TAB(5) " AIR TEMPERATURE (F) = " ;
522 LPRINT USING F1$;TAI,(TAI-32)/1.8;LPRINT " C"

```

```

524 LPRINT TAB(5) " RELATIVE HUMIDITY (%) = ";
526 LPRINT USING F1$;RHI*100
528 LPRINT TAB(5) " PELLET TEMPERATURE (F) = ";
530 LPRINT USING F1$;TPI,(TPI-32)/1.8;:LPRINT " C"
532 LPRINT TAB(5) " MOISTURE CONTENT (% WB) = ";
534 LPRINT USING F1$;MCIW;
536 LPRINT USING F1$;MCID*100;:LPRINT " %DB"
538 LPRINT TAB(5) " PELLET DIAMETER (In.) = ";
540 LPRINT USING F2$;DIAI;:LPRINT USING F1$;DIAI*25.4;
542 LPRINT " MM"
544 LPRINT TAB(6) "AIR FLOW (CFM/FT2) = ";
546 LPRINT USING F1$;CFM;
548 LPRINT USING F1$;VA;:LPRINT " M/S"
550 LPRINT TAB(5) " COOLER DEPTH (FT) = ";
552 LPRINT USING F1$;BED,BED*30.48;:LPRINT " CM"
554 LPRINT TAB(5) " DELTA x (In.) = ";
556 LPRINT USING F1$;DELX*12;
558 LPRINT USING F1$;DELX*30.48;:LPRINT " CM "
560 LPRINT TAB(5) " DELTA t (Min.) = ";
562 LPRINT USING F1$;DT*60
564 LPRINT
566 RETURN
568 REM
570 LPRINT:LPRINT TAB(6) "TIME (Min.) = ";:LPRINT USING F1$;L*60
572 LPRINT: LPRINT TAB(5) " BED DEPTH cm";
574 FOR Y=0 TO (12*BED) STEP (2*BED):LPRINT USING F1$;Y*2.54;
576 NEXT Y
578 LPRINT:LPRINT:LPRINT TAB(5) " PEL.TEMP. C ";
580 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;(TPT(Y,0)-KT)/1.8;
582 NEXT Y:LPRINT
584 LPRINT TAB(5) " M.C. %DB ";
586 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;MC(Y,0)*100;:NEXT Y
588 LPRINT TAB(5) " M.C. %WB ";:FOR Y=0 TO XT STEP XPR
590 W=MC(Y,0):LPRINT USING F1$;(W/(1+W))*100;:NEXT Y
592 IF L = 0 GOTO 604
594 LPRINT: LPRINT TAB(5) " EQ.MC. %DB ";
596 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;EMCD(Y)*100;:NEXT Y
598 LPRINT: LPRINT TAB(5) " REL. HUMID. ";
600 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;RH(Y)*100;:NEXT Y
602 LPRINT
604 LPRINT TAB(5) " ABS. HUMID. ";:FOR Y=0 TO XT STEP XPR:
606 LPRINT USING " .####"; H(Y);:NEXT Y:LPRINT
608 LPRINT:LPRINT TAB(11) "AVE. TEMP. (C) = ";:LPRINT USING F1$;TPA;
610 LPRINT " AVE. MC. (%DB) = ";:LPRINT USING F1$;MCAVE*100
612 LPRINT TAB(10) STRING$(54,"*")
614 LPRINT:LPRINT
616 RETURN

```

HMB MODEL OUTPUT SAMPLE

INITIAL CONDITIONS

AIR TEMPERATURE (F) = 80.00 26.67 C
 RELATIVE HUMIDITY (%) = 55.00
 PELLET TEMPERATURE (F) = 150.00 65.56 C
 MOISTURE CONTENT (% WB) = 17.00 20.48 %DB
 PELLET DIAMETER (In.) = .1875 4.76 MM
 AIR FLOW (CFM/FT2) = 100.00 0.51 M/S
 COOLER DEPTH (FT) = 1.00 30.48 CM
 DELTA x (In.) = 0.25 0.63 CM
 DELTA t (Min.) = 1.00

TIME (Min.) = 0.00

BED DEPTH cm	0.00	5.08	10.16	15.24	20.32	25.40	30.48
PEL.TEMP. C	46.11	65.56	65.56	65.56	65.56	65.56	65.56
M.C. %DB	20.48	20.48	20.48	20.48	20.48	20.48	20.48
M.C. %WB	17.00	17.00	17.00	17.00	17.00	17.00	17.00
ABS. HUMID.	.0120	.0120	.0120	.0120	.0120	.0120	.0120

AVE. TEMP. (C) = 65.16 AVE. MC. (%DB) = 20.48

TIME (Min.) = 20.00

BED DEPTH cm	0.00	5.08	10.16	15.24	20.32	25.40	30.48
PEL.TEMP. C	26.58	26.53	26.48	26.44	26.47	26.55	26.61
M.C. %DB	16.87	17.16	17.49	17.85	18.16	18.24	18.09
M.C. %WB	14.44	14.65	14.88	15.14	15.37	15.43	15.32
EQ.MC. %DB	14.09	14.61	15.18	15.82	16.38	16.52	16.26
REL. HUMID.	55.00	58.64	62.46	66.46	69.77	70.61	69.16
ABS. HUMID.	.0120	.0128	.0136	.0144	.0152	.0153	.0150

AVE. TEMP. (C) = 26.51 AVE. MC. (%DB) = 17.73

APPENDIX D

PARTIAL DIFFERENTIAL EQUATIONS MODEL AND SAMPLE OUTPUT

PARTIAL DIFFERENTIAL EQUATIONS MODEL
FOR STATIONARY-BED PELLET COOLER

```

100 CLS
102 REM MODEL #2 - PARTIAL DIFFERENTIAL EQUATIONS (PDE)
104 REM COOLING OF A FIXED BED OF PELLETS
106 REM PROGRAM: PELLET2
108 REM
110 REM THIS MODEL COMPUTES AIR TEMPERATURES, RELATIVE HUMIDITY, ABSOLUTE
112 REM HUMIDITY, PELLET MOISTURE CONTENTS AND TEMPERATURES OF A FIXED
114 REM BED OF PELLETS. ALSO DETERMINES MOISTURE CONTENT AND TEMPERATURE
116 REM GRADIENTS WITHIN A PELLET AT EACH DX LOCATION INSIDE THE BED.
118 REM
120 REM JOAO BIAZI - SUMMER/86 - MSU - EAST LANSING
122 REM
124 DIM T(15,65),TA(201),TC(201,2),TS(201),TAV(201),MT(15,65),MS(201)
126 DIM MC(201,2),H(201),RH(201),EMCD(201),TPT(201,2),MAV(201,2)
128 DIM LA(5),AA(5),B(5),AR(5),MCEQ(201)
130 DIM TG(15), MCG(15)
132 REM INPUT BLOCK
134 CLS:LOCATE 3,5: PRINT " PDE MODEL: INPUT VALUES": PRINT
136 INPUT " Air Temperature (F) " = ", TAI
138 INPUT " Relative Humidity (%) " = ", RHI
140 INPUT " Air Flow Rate (CFM/FT2) " = ", CFM
142 INPUT " Pellet Temperature (F) " = ", TPI
144 INPUT " Initial Moisture Content (XWB) " = ", MCIW
146 INPUT " Pellet Diameter (In.) " = ", DIAI
148 INPUT " Cooling Time (Min) " = ", TI
150 PRINT
152 REM DIAMETER IN FOOT, RADIUS IN METER
154 DIAF=DIAI/12:R=(DIAI/2)*.0254
156 REM CONSTANTS OF MOIST. CONTENT EQN..ROOTS BESSEL FC.
158 KL=3:FOR I=1 TO KL: READ LA(I)
160 AA(I)=LA(I)*LA(I):B(I)=4/AA(I):AR(I)=-AA(I)/(R*R):NEXT I
162 DATA 2.405,5.52,8.654
164 REM AIR AND VAPOR CONSTANTS
166 CW=1:CA=.2405:CV=.448:VI=.0443:AIRD=.063415
168 REM SPECIFIC SURFACE AREA (FT2/FT3)
170 SA=48/DIAI
172 REM PELLET DENSITY (LB/FT3); (KG/M3)
174 PDEE=42:PDEM=PDEE*16.0185
176 REM AIR VELOCITY (M/S)
178 VA=(CFM*.3048)/60
180 REM BED=FEET; AREA= FT2; POROSITY
182 BED=1:AREA=1:PO=.44
184 REM DELX=FT; # LAYERS/FOOT; PRINTING COUNT.
186 DELX=.0208:XT=INT(BED/DELX):XPR=(XT)/6
188 REM TI AND DT = HOUR
190 TI=TI/60:DT=.5/60

```

```

192 REM CONSTANTS OF SUBROUTINE FINITE DIFF.FORMULAS
194 REM DELR=METER;DELT=SECONDS
196 DELR=.0005;DELT=.5;TIME=15
198 IF CFM>50 THEN KTI=18 ELSE KTI=15
200 TTM =KTI/(DT*60)
202 TT=TIME/DELT
204 M=INT(R/DELR)+1
206 B=1-1/(2*M);C=1+1/(2*M)
208 REM RHI=DECIMAL; MC=DECIMAL DRY BASIS
210 RHI=RHI/100;MCID=MCIW/(100-MCIW)
212 RHC=.98
214 REM COMPUTE INLET ABSOLUTE HUMIDITY AND SPEC.VOLUME
216 IJ=1;DB=TAI;RH=RHI;GOSUB 644;HI=HU;SVI=SV
218 REM COMPUTE AIR FLOW (LB/Hr), REYNOLDS'#, SCHMIDT'#
220 GA=(CFM*60)/(AREA*SVI)
222 REN=(GA*DIAF)/VI
224 SCN=VI/(AIRD*DIAF)
226 REM HEAT TRANSFER COEFF. (BTU/Hr FT2 F)
228 HT=CA*GA*.992*(REN)^(-.34)
230 HTM=5.677 * HT
232 REM MASS TRANSF. COEFF. (LB/Hr FT2)
234 HM=GA*15.5*(REN)^(-1)*(SCN)^(-2/3)*(1-PO)^1.2
236 REM MASS TRANSF. COEFF. (M/Hr)
238 HM=HM*(4.8823/PDEM)
240 REM CONSTANTS OF AIR, PELLET TEMP. AND ABS.HUM. EQNS.
242 IF CFM>50 THEN G=2.4; ELSE G=1.25
244 C1=PDEE*DELX/(GA*DT);C2=DT/(PDEE*G)
246 C3=(HT*SA*DELX)/GA; C4=HT*SA; C5=GA/DELX
248 REM PRINTING FORMATS
250 F1$=" ###.##";F2$=" .####";F3$=" ##.## "
252 REM PRINT INITIAL CONDITIONS
254 CLS; LOCATE 5,2
256 PRINT
258 PRINT;PRINT TAB(11) "INITIAL CONDITIONS ";PRINT
260 PRINT TAB(6) "AIR TEMPERATURE (F) = ";
262 PRINT USING F1$;TAI,(TAI-32)/1.8;PRINT " C"
264 PRINT TAB(6) "RELATIVE HUMIDITY (%) = ";
266 PRINT USING F1$;RHI*100
268 PRINT TAB(6) "PELLET TEMPERATURE (F) = ";
270 PRINT USING F1$;TPI,(TPI-32)/1.8;PRINT " C"
272 PRINT TAB(6) "MOISTURE CONTENT (X DB) = ";
274 PRINT USING F1$;MCID*100;PRINT USING F1$;MCIW;
276 PRINT " XWB"
278 PRINT TAB(6) "PELLET DIAMETER (In.) = ";
280 PRINT USING F2$;DIAI;PRINT USING F1$;DIAI*25.4;
282 PRINT " mm"
284 PRINT TAB(6) "AIR FLOW (CFM/FT2) = ";
286 PRINT USING F1$;CFM;PRINT USING F1$;VA;PRINT " M/S "
288 PRINT TAB(6) "HEAT T.COEF. (BTU/FT2Hr F) = ";
290 PRINT USING F1$;HT,HTM;PRINT " (W/M2 K)"
292 PRINT TAB(6) "COOLER DEPTH (FT) = ";
294 PRINT USING F1$;BED,BED*30.48;PRINT " CM"
296 D1=DELX*12;D2=DELX*30.48
298 PRINT TAB(6) "DELTA X (In.) = ";
300 PRINT USING F1$;D1;PRINT USING F1$;D2;PRINT " CM"

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302 PRINT TAB(6) "DELTA t (Min.) = ";
304 PRINT USING F1$;DT*60
306 PRINT
308 LPRINT: LPRINT: LPRINT
310 LPRINT TAB(10) " INITIAL CONDITIONS ":LPRINT
312 LPRINT TAB(6) "AIR TEMPERATURE (F) = ";
314 LPRINT USING F1$;TAI,(TAI-32)/1.8;:LPRINT " C"
316 LPRINT TAB(6) "RELATIVE HUMIDITY (%) = ";
318 LPRINT USING F1$;RHI*100
320 LPRINT TAB(6) "PELLET TEMPERATURE (F) = ";
322 LPRINT USING F1$;TPI,(TPI-32)/1.8;:LPRINT " C"
324 LPRINT TAB(6) "MOISTURE CONTENT (% DB) = ";
326 LPRINT USING F1$;MCID*100;:LPRINT USING F1$;MCIDW;
328 LPRINT " %WB"
330 LPRINT TAB(6) "PELLET DIAMETER (In.) = ";
332 LPRINT USING F2$;DIAI;:LPRINT USING F1$;DIAI*25.4;
334 LPRINT " mm"
336 LPRINT TAB(6) "AIR FLOW (CFM/FT2) = ";
338 LPRINT USING F1$;CFM;:LPRINT USING F1$;VA;:LPRINT " M/S "
340 LPRINT TAB(6) "HEAT T.COEF. (BTU/FT2 HrF)= ";
342 LPRINT USING F1$;HT,HTM;:LPRINT " (W/M2 K) "
344 LPRINT TAB(6) "MASS T.COEF. (M/Hr) = ";
346 LPRINT USING F2$;HM
348 LPRINT TAB(6) "COOLER DEPTH (FT) = ";
350 LPRINT USING F1$;BED,BED*30.48;:LPRINT " CM"
352 LPRINT TAB(6) "DELTA x (In.) = ";
354 LPRINT USING F1$;D1;:LPRINT USING F1$;D2;:LPRINT " CM"
356 LPRINT TAB(6) "DELTA t (Min.) = ";
358 LPRINT USING F1$;DT*60
360 LPRINT
362 REM
364 REM AIR TEMPERATURE AT TIME=0; INITIALIZE ARRAY POSITIONS
366 TA(0)=TAI;RH(0)=RHI;TPT(0,0)=(TAI+TPI)/2
368 TC(0,0)=TPT(0,0);TS(0)=TPT(0,0);TAV(0)=TPT(0,0)
370 FOR X=0 TO XT:TC(X+1,0)=TPI:TPT(X+1,0)=TPI:MC(X,0)=MCID
372 MAV(X,0)=MCID;TS(X+1)=TPI:TAV(X+1)=TPI:H(X)=HI
374 TA(X+1)=TA(X)-(C3/(CA+CV*H(X)))*(TA(X)-TS(X))
376 NEXT X
378 CLS: LOCATE 1,2
380 PRINT:PRINT TAB(6) "TIME (Min.) = 0.00":PRINT
382 PRINT TAB(5) " BED DEPTH cm";
384 FOR X=0 TO (12*BED) STEP (2*BED):PRINT USING F1$;X*2.54;
386 NEXT X:PRINT:PRINT
388 PRINT TAB(6) "AIR TEMP. ";:FOR X=0 TO XT STEP XPR
390 PRINT USING F1$;(TA(X)-32)/1.8;:NEXT X:PRINT
392 PRINT TAB(6) "PELLET TEMP. ";:FOR X=0 TO XT STEP XPR
394 PRINT USING F1$;(TC(X,0)-32)/1.8;:NEXT X:PRINT
396 PRINT TAB(5) " MOIS.CONT. ";
398 FOR X=0 TO XT STEP XPR:PRINT USING F1$;MC(X,0)*100;:NEXT X
400 PRINT:PRINT TAB(5) " ABS. HUMID. ";
402 FOR X=0 TO XT STEP XPR:PRINT USING F2$;H(X);:NEXT X:PRINT
404 REM PRINT: PRINT TAB(10) STRING$(53,"*"): PRINT
406 LPRINT:LPRINT TAB(6) "TIME (Min.) = 0.00":LPRINT
408 LPRINT TAB(5) " BED DEPTH cm";
410 FOR X=0 TO (12*BED) STEP (2*BED):LPRINT USING F1$;X*2.54;

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412 NEXT X:LPRINT:LPRINT
414 LPRINT TAB(6) "AIR TEMP. ";FOR X=0 TO XT STEP XPR
416 LPRINT USING F1$;(TA(X)-32)/1.8;NEXT X:LPRINT
418 LPRINT TAB(6) "PELLET TEMP.";FOR X=0 TO XT STEP XPR
420 LPRINT USING F1$;(TC(X,0)-32)/1.8;NEXT X:LPRINT
422 LPRINT TAB(5) " MOIS.CONT. ";
424 FOR X=0 TO XT STEP XPR:LPRINT USING F1$;MC(X,0)*100;NEXT X
426 LPRINT:LPRINT TAB(5) " ABS. HUMID. ";
428 FOR X=0 TO XT STEP XPR:LPRINT USING F2$;H(X);NEXT X:LPRINT
430 LPRINT:LPRINT TAB(10) STRING$(53,"*"); LPRINT
432 REM
434 CPRI=0:PTI=1/(DT*60)
436 REM TIME LOOP
438 FOR L = DT TO TI STEP DT
440 CPRI=CPRI+1:SMC=0: STA=0
442 LOCATE 22,5
444 PRINT " ELAPSED TIME = ";PRINT USING "##.##"; L*60;
446 PRINT " min.:";PRINT " COMPUTING CONDITIONS AT "
448 REM DEPTH LOOP
450 FOR X = 0 TO XT
452 LOCATE 22,56
454 PRINT USING " ##.##";((X*30.48*BED)/XT); PRINT " cm."
456 REM EQUILIBRIUM MOISTURE CONTENT EQUATIONS
458 TPC=(TAV(X)-32)*(5/9)
460 REM NELLIST EQUATION
462 REM EMCD(X)=.191-.055*LOG(1-RH(X))-.028*LOG(TPC)
464 REM HENDERSON EQUATION
466 REM EMCD(X)=(-LOG(1-RH(X))/(6.66*(TPC+22.12)))^(1/3.11)
468 REM CHUNG-PFOST EQUATION
470 EMCD(X)=.277-.042*LOG(-(TPC+13.3)*LOG(RH(X)))
472 REM DIFFUSION COEFFICIENT EQUATION
474 DIC=1.015E-05*EXP(-547/(TPC+273.15))
476 REM MOISTURE CONTENT DIFFERENTIAL EQN.
478 SUMM=0:FOR I = 1 TO KL
480 SUMC=B(I)*EXP(AR(I)*DIC*L)
482 SUMM=SUMM+SUMC:NEXT I
484 MCEQ(X)=EMCD(X)+(MCID-EMCD(X))*SUMM
486 REM MOISTURE CONTENT - FINITE-DIFF. FORMULAS
488 MCT=MC(X,0):EMC=EMCD(X)
490 AM=(DIC*DT)/(DELR*DELR)
492 GOSUB 608
494 MC(X,1)=MT(0,NI-1):MS(X)=MT(M,NI):MAV(X,1)=MAVE
496 SMC=SMC+MAV(X,1)
498 REM ABSOLUTE HUMIDITY EQUATION
500 H(X+1)=H(X)-C1*(MC(X,1)-MC(X,0))
502 REM PELLET TEMPERATURE EQUATIONS
504 P=MAV(X,0)
506 K=.1133-2.936*(P*P)+25.44*(P*P*P)-38.71*(P*P*P*P)
508 CP=4180*(.343+P)/(1+P):CPE=CP/4186.69
510 A=(K*DELT)/(PDEM*CP*(DELR*DELR))
512 REM
514 TPK=TPT(X,0)+459.69
516 HFG=(1056.5-.55*(TPK-520))*(1+23*EXP(-4*TPK*P))
518 DTEMP=TA(X)-TS(X):AUX=CPE+CW*P:AUX1=HFG+CV*DTEMP
520 DHT=H(X+1)-H(X)

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522 TPT(X,1)=TPT(X,0)+C2*((C4*DTEMP)-(AUX1+C5)*DHT)/AUX)
524 REM
526 TAC=TA(X);TP=TPT(X,0);GOSUB 572
528 TC(X,1)=T(0,N-1);TS(X)=T(M,N);TAV(X)=TAVE
530 REM AIR TEMPERATURE EQUATION
532 TA(X+1)=TA(X)-(C3/(CA+CV*H(X)))*(TA(X)-TS(X))
534 STA=STA+TPT(X,1)
536 REM RELATIVE HUMIDITY
538 IJ=2;DB=TA(X+1);HU=H(X+1);GOSUB 644;RH(X+1)=RH
540 IF RH>RHC THEN RH(X+1)=RHC
542 NEXT X
544 MCAVE=SMC/X;TPA=((STA/X)-32)/1.8
546 FOR X=0 TO XT:MC(X,0)=MC(X,1);TC(X,0)=TC(X,1)
548 TPT(X,0)=TPT(X,1);MAV(X,0)=MAV(X,1);NEXT X
550 REM
552 GOSUB 704
554 IF PTI=CPRI THEN CPRI=0;GOSUB 776
556 NEXT L
558 LPRINT:LPRINT
560 LOCATE 23,5
562 INPUT "DO YOU WANT TO INPUT NEW DATA? (Y OR N) ",ND$
564 IF ND$="N" OR ND$="n" GOTO 568
566 IF ND$="Y" OR ND$="y" GOTO 134 ELSE GOTO 560
568 END
570 REM SUBROUTINE FINITE DIFFERENCE FORMULAS
572 REM SUBROUTINE PELLET TEMPERATURES
574 FOR J=0 TO M:T(J,0)=TP:NEXT J
576 D=(2*A*HTM*C*DELR)/K
578 T1=(1+2*M-4*A)/(1+2*M);T2=4*A/(1+2*M);T3=A*B
580 T4=1-2*A;T5=A*C;T6=2*A;T7=1-2*A-D
582 FOR N=0 TO TT
584 SUM = 0
586 FOR J=1 TO M
588 T(0,N+1)=T1*T(0,N)+T2*T(1,N)
590 T(J,N+1)=T3*T(J-1,N)+T4*T(J,N)+T5*T(J+1,N)
592 T(M,N+1)=T6*T(M-1,N)+T7*T(M,N)+D*TAC
594 SUM=SUM+T(J,N+1)
596 NEXT J
598 TAVE=(SUM+T(0,N+1))/J
600 NEXT N
602 IF X>0 GOTO 606
604 FOR IG=0 TO M: TG(IG)=T(IG,N);NEXT IG
606 RETURN
608 REM SUBROUTINE PELLET MOISTURE CONTENT
610 FOR J=0 TO M:MT(J,0)=MCT:NEXT J
612 D=(2*AM*HM*C*DELR)/DIC
614 M1=(1+2*M-4*AM)/(1+2*M);M2=4*AM/(1+2*M);M3=AM*B
616 M4=1-2*AM;M5=AM*C;M6=2*AM;M7=1-2*AM-D
618 FOR NI=0 TO TTM
620 SUM = 0
622 FOR J=1 TO M
624 MT(0,NI+1)=M1*MT(0,NI)+M2*MT(1,NI)
626 MT(J,NI+1)=M3*MT(J-1,NI)+M4*MT(J,NI)+M5*MT(J+1,NI)
628 MT(M,NI+1)=M6*MT(M-1,NI)+M7*MT(M,NI)+D*EMC
630 SUM=SUM+MT(J,NI+1)

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632 NEXT J
634 HAVE=(SUM+MT(0,NI+1))/J
636 NEXT NI
638 IF X>0 GOTO 642
640 FOR IG=0 TO M: MC6(IG)=MT(IG,NI):NEXT IG
642 RETURN
644 REM SUBROUTINE PSYCHART(DB,WB,DP,RH,HU,PV,SV,HFG)
646 IF DB>212 GOTO 652
648 A#=92.29778#:B#=.2226883#:C#=12.88743#:D#=9.415002#
650 GOTO 654
652 A#=44.11702#:B#=.2949225#:C#=21.77737#:D#=55.98703#
654 IF DB>180 GOTO 662
656 B1#=-7.37013E-06:B2#=-3.53885E-03:B3#=.827522#:B4#=-3.89627E-06
658 B5#=-2.60113E-06:B6#=-1.404191#
660 GOTO 666
662 B1#=-2.49546E-06:B2#=-2.04326E-03:B3#=.707415#:B4#=-1.88247E-06
664 B5#=-2.00086E-03:B6#=-1.442215#
666 T=DB+459.69
668 PS=EXP(54.6329#-(12301.688#/T)-5.16923#*LOG(T))
670 IF IJ=2 THEN PV=HU*14.696/(.621+HU):RH=PV/PS:GOTO 674
672 PV=PS*RH
674 DP=A#*PV^B#+C#*LOG(PV) +D#
676 DTD=DB-DP
678 WB=DP+(B1#*DTD^3+B2#*DTD^2+B3#*DTD)*EXP((B4#*DTD+B5#)*DP^B6#)
680 IF IJ=2 GOTO 684
682 HU=.6219*(PV/(14.696-PV))
684 SV=(53.35#*(DB+459.69))/(144*(14.696-PV))
686 GOTO 702
688 T=DB
690 IF (T>32) AND (T<150) THEN GOTO 696 ELSE IF T>150 GOTO 700
692 HFG=1220.844#-.05077#*T
694 GOTO 702
696 HFG=1075.8965#-.56983#*(T-32)
698 GOTO 702
700 HFG=(1354673.214#-.9125275587#*(T+459.69)^2)^.5
702 RETURN
704 REM SUBROUTINE PRINT = SCREEN
706 CLS: LOCATE 1,2
708 PRINT:PRINT TAB(6) "TIME (Min.) = ";PRINT USING F3%;L*60
710 PRINT TAB(5) " BED DEPTH cm";
712 FOR Y=0 TO (12*BED) STEP (2*BED):PRINT USING F1%;Y*2.54;
714 NEXT Y:PRINT:PRINT:PRINT TAB(5) " AIR TEMP. C ";
716 FOR Y=0 TO XT STEP XPR:PRINT USING F1%;(TA(Y)-32)/1.8;NEXT Y
718 PRINT:PRINT TAB(5) " PELLET TEMPERATURES (C)"
720 PRINT TAB(5) " AT CENTER ";
722 FOR Y=0 TO XT STEP XPR:PRINT USING F1%;(TC(Y,0)-32)/1.8;NEXT Y
724 PRINT:PRINT TAB(5) " AT SURFACE ";
726 FOR Y=0 TO XT STEP XPR:PRINT USING F1%;(TS(Y)-32)/1.8;NEXT Y
728 PRINT:PRINT TAB(5) " AVERAGE ";
730 FOR Y=0 TO XT STEP XPR:PRINT USING F1%;(TAV(Y)-32)/1.8;NEXT Y
732 PRINT:PRINT TAB(5) " TEMP. EQN. ";
734 FOR Y=0 TO XT STEP XPR:PRINT USING F1%;(TPT(Y,0)-32)/1.8;NEXT Y
736 PRINT:PRINT TAB(5) " PELLET MOISTURE CONTENTS (% DB)"
738 PRINT TAB(5) " AT CENTER ";
740 FOR Y=0 TO XT STEP XPR:PRINT USING F1%;MC(Y,0)*100;NEXT Y:PRINT

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742 PRINT TAB(5) " AT SURFACE ";
744 FOR Y = 0 TO XT STEP XPR: PRINT USING F1$; MS(Y)*100;; NEXT Y
746 PRINT: PRINT TAB(5) " AVERAGE DB. ";
748 FOR Y=0 TO XT STEP XPR:PRINT USING F1$;MAV(Y,0)*100;;NEXT Y:PRINT
750 PRINT TAB(5) " AVERAGE %WB ";
752 FOR Y=0 TO XT STEP XPR:W=MAV(Y,0):PRINT USING F1$;(W*100)/(1+W);
754 NEXT Y:PRINT: PRINT TAB(5) " MC.D. EQN. ";
756 FOR Y=0 TO XT STEP XPR:PRINT USING F1$;MCEQ(Y)*100;;NEXT Y
758 PRINT:PRINT TAB(5) " EQ.MO.CONT. ";
760 FOR Y=0 TO XT STEP XPR:PRINT USING F1$;EMCD(Y)*100;;NEXT Y
762 PRINT:PRINT TAB(5) " REL. HUMID. ";
764 FOR Y=0 TO XT STEP XPR:PRINT USING F1$;RH(Y)*100;;NEXT Y
766 PRINT:PRINT TAB(5) " ABS. HUMID. ";
768 FOR Y=0 TO XT STEP XPR:PRINT USING F2$;H(Y);;NEXT Y:PRINT
770 PRINT:PRINT TAB(7) "AVE.PEL.TEMP. (C) ";:PRINT USING F1$;TPA;
772 PRINT " AVE.MC. (%DB) = ";:PRINT USING F1$;MCAVE*100
774 RETURN
776 REM SUBROUTINE PRINT = PRINTER
778 LPRINT:LPRINT TAB(5) " TIME (Min.) = ";:LPRINT USING F1$;L*60
780 LPRINT: LPRINT TAB(5) " BED DEPTH cm";
782 FOR Y=0 TO (12*BED) STEP (2*BED):LPRINT USING F1$;Y*2.54;
784 NEXT Y:LPRINT:LPRINT: LPRINT TAB(5) " AIR TEMP. C ";
786 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$; (TA(Y)-32)/1.8;;NEXT Y
788 LPRINT:LPRINT TAB(5) " PELLET TEMPERATURES (C)"
790 LPRINT TAB(5) " AT CENTER ";
792 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;(TC(Y,0)-32)/1.8;;NEXT Y
794 LPRINT:LPRINT TAB(5) " AT SURFACE ";
796 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;(TS(Y)-32)/1.8;;NEXT Y
798 LPRINT: LPRINT TAB(5) " AVERAGE ";
800 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;(TAV(Y)-32)/1.8;;NEXT Y
802 LPRINT:LPRINT TAB(5) " TEMP. EQN. ";
804 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;(TPT(Y,0)-32)/1.8;;NEXT Y
806 LPRINT:LPRINT TAB(5) " PELLET MOISTURE CONTENTS (% DB)"
808 LPRINT TAB(5) " AT CENTER ";
810 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;MC(Y,0)*100;;NEXT Y
812 LPRINT:LPRINT TAB(5) " AT SURFACE ";
814 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;MS(Y)*100;;NEXT Y
816 LPRINT: LPRINT TAB(5) " AVERAGE ";
818 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;MAV(Y,0)*100;;NEXT Y
820 LPRINT:LPRINT TAB(5) " AVERAGE %WB ";
822 FOR Y=0 TO XT STEP XPR:W=MAV(Y,0):LPRINT USING F1$;(W*100)/(1+W);
824 NEXT Y:LPRINT: LPRINT TAB(5) " MC.D. EQN. ";
826 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;MCEQ(Y)*100;;NEXT Y
828 LPRINT: LPRINT TAB(5) " EQ.MO.CONT. ";
830 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;EMCD(Y)*100;;NEXT Y
832 LPRINT:LPRINT: LPRINT TAB(5) " REL. HUMID. ";
834 FOR Y=0 TO XT STEP XPR:LPRINT USING F1$;RH(Y)*100;;NEXT Y
836 LPRINT:LPRINT TAB(5) " ABS. HUMID. ";:FOR Y=0 TO XT STEP XPR:
838 LPRINT USING F2$;H(Y);;NEXT Y:LPRINT
840 LPRINT:LPRINT TAB(7) "AVE.PEL.TEMP. (C) ";:LPRINT USING F1$;TPA;
842 LPRINT " AVE.MC. (%DB) = ";:LPRINT USING F1$;MCAVE*100
844 LPRINT TAB(6) "MOISTURE CONT. INSIDE A PELLET AT THE BOTTOM LAYER"
846 LPRINT TAB(4) " ";:LPRINT USING F1$;MCG(0)*100;
848 FOR Q=1 TO M:LPRINT USING F1$;MCG(Q)*100;;NEXT Q:LPRINT
850 LPRINT TAB(6) "MOISTURE CONT. INSIDE A PELLET AT THE TOP LAYER"

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852 LPRINT TAB(4) " ";LPRINT USING F1$;MT(0,NI-1)*100;
854 FOR Q=1 TO M:LPRINT USING F1$;MT(Q,NI-1)*100;:NEXT Q:LPRINT
856 LPRINT TAB(6) "TEMPERATURE INSIDE A PELLET AT THE BOTTOM LAYER"
858 LPRINT TAB(5);
860 FOR Q=0 TO M:LPRINT USING F1$;(TG(Q)-32)/1.8;:NEXT Q
862 LPRINT TAB(6) "TEMPERATURE INSIDE A PELLET AT THE TOP LAYER"
864 LPRINT TAB(5);
866 FOR Q=0 TO M:LPRINT USING F1$;(T(Q,N)-32)/1.8;:NEXT Q
868 LPRINT TAB(10) STRING$(54,"*")
870 LPRINT:LPRINT
872 RETURN
```

PDE MODEL OUTPUT SAMPLE

INITIAL CONDITIONS

AIR TEMPERATURE (F)	=	80.00	26.67 C
RELATIVE HUMIDITY (%)	=	55.00	
PELLET TEMPERATURE (F)	=	150.00	65.56 C
MOISTURE CONTENT (% DB)	=	20.48	17.00 %WB
PELLET DIAMETER (In.)	=	.1875	4.76 mm
AIR FLOW (CFM/FT2)	=	100.00	0.51 M/S
HEAT T.COEF. (BTU/FT2 HrF)	=	18.68	106.04 (W/M2 K)
MASS T.COEF. (M/Hr)	=	.0126	
COOLER DEPTH (FT)	=	1.00	30.48 CM
DELTA x (In.)	=	0.25	0.63 CM
DELTA t (Min.)	=	0.50	

TIME (Min.) = 0.00

BED DEPTH cm 0.00 5.08 10.16 15.24 20.32 25.40 30.48

AIR TEMP.	26.67	65.56	65.56	65.56	65.56	65.56	65.56
PELLET TEMP.	46.11	65.56	65.56	65.56	65.56	65.56	65.56
MOIS.CONT.	20.48	20.48	20.48	20.48	20.48	20.48	20.48
ABS. HUMID.	.0120	.0120	.0120	.0120	.0120	.0120	.0120

TIME (Min.) = 20.00

BED DEPTH cm	0.00	5.08	10.16	15.24	20.32	25.40	30.48
AIR TEMP. C	26.67	25.54	24.73	24.16	23.78	23.52	23.36
PELLET TEMPERATURES (C)							
AT CENTER	26.18	25.19	24.49	24.00	23.67	23.45	23.31
AT SURFACE	26.49	25.42	24.64	24.10	23.74	23.50	23.34
AVERAGE	26.32	25.30	24.56	24.05	23.70	23.47	23.33
TEMP. EQN.	26.14	25.17	24.47	23.99	23.66	23.45	23.32
PELLET MOISTURE CONTENTS (% DB)							
AT CENTER	19.12	18.69	18.49	18.33	18.19	18.07	17.97
AT SURFACE	14.49	15.37	16.11	16.69	17.12	17.43	17.63
AVERAGE	17.49	17.53	17.65	17.75	17.82	17.85	17.85
AVERAGE XWB	14.88	14.91	15.00	15.08	15.12	15.14	15.15
MC.D. EQN.	16.89	17.46	17.92	18.29	18.56	18.75	18.88
EQ.MO.CONT.	14.12	15.11	15.92	16.56	17.04	17.38	17.60
REL. HUMID.	55.00	61.10	65.74	69.19	71.60	73.21	74.24
ABS. HUMID.	.0120	.0125	.0128	.0130	.0132	.0133	.0133

AVE.PEL.TEMP. (C) 24.24 AVE.MC. (%DB) = 17.71
 MOISTURE CONT. INSIDE A PELLET AT THE TOP LAYER
 17.97 17.96 17.93 17.86 17.76 17.63
 TEMPERATURE INSIDE A PELLET AT THE TOP LAYER
 23.31 23.32 23.32 23.33 23.34 23.34

APPENDIX E

BMDPAR SUBROUTINE: EMC and D ESTIMATION

BMDPAR SUBROUTINE: EMC and D ESTIMATION

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100= / PROBLEM      TITLE IS 'PELLETS:EMC AND D'.
110= / INPUT        VARIABLES = 4.
120=                UNIT = 55.
130=                FORMAT IS '(F4.1,1X,F4.1,1X,F4.1,1X,F4.1)'.
140= / VARIABLE     NAMES = XMT,XM,T,TI.
150= / TRANSFORM    TI = TI/60.
160= / REGRESS      DEPENDENT = XMT.
170=                PARAMETERS = 2.
180=                PRINT = XMT,TI.
190=                ITERATIONS = 100.
200=                CONVERGE = .0001.
210=                HALVING = 20.
220= / PARAMETER    INITIAL = 10.,000001.
230=                MAXIMUM = 100,10.
240=                NAMES = EMC,D.
250= / FUN          ALP1=2.405**2$ALP2=5.52**2$ALP3=8.654**2.
260=                ALP4=11.792**2$ALP5=14.931**2$ALP6=18.071**2.
270=                ALP7=21.22**2$ALP8=24.35**2$ALP9=27.49**2.
280=                ALP10=30.63**2.
290=                A=4/ALP1$B=4/ALP2$C=4/ALP3$E=4/ALP4$G=4/ALP5.
300=                D=4/ALP6$P=4/ALP7$Q=4/ALP8$R=4/ALP9$S=4/ALP10.
310=                DIA = .1875.
320=                RMS = ((DIA/2)*.0254)**2.
330=                C1=-ALP1/RMS$C2=-ALP2/RMS$C3=-ALP3/RMS.
340=                C4=-ALP4/RMS$C5=-ALP5/RMS$C6=-ALP6/RMS.
350=                C7=-ALP7/RMS$C8=-ALP8/RMS$C9=-ALP9/RMS.
360=                C10=-ALP10/RMS.
370=                F=EMC+(XM-EMC)*(A*EXP(C1*D*T)+(B*EXP(C2*D*T)+
                    (C*EXP(C3*D*T))).
380= / PLOT         VARIABLE IS XMT.
390=                RESIDUAL.
400=                SIZE = 20, 12.
410= / SAVE         CODE = T3B.
420=                UNIT = 9.
430=                NEW.
440= / END

```