107
519
THS

RESEARCHES IN THERMODYNAMICS

THESIS FOR DEGREE OF M. S.

ERROL E. EMSHWILLER

1928

THESIS

A Thesis on

RESEARCHES IN THERMODYNAMICS

submitted to

The Department of Mechanical Engineering

(Professor H. B. Dirks)

and

The Department of Graduate Work

(Dr. R. C. Huston)

Michigan State College

East Lansing.

approved 6/4/28
H.B. Dirks.

by

Errol E. Emshwiller

Candidate for Degree of Master of Science

in Mechanical Engineering

June 4, 1928.

PREFACE

The author, in taking graduate work in the power production side of Mechanical Engineering, and especially in the Thermodynamic and Engine Design divisions of said power production, felt the necessity of getting a more thorough understanding of the power-producing methods and machines used and practically or theoretically capable of being used, than can be obtained in the ordinary undergraduate studies in Thermodynamics, Heat Engines, Automotive Design, etc; and some of the main points brought out by his studies towards getting this understanding are set down in this thesis. Most of the graduate work taken being along the lines of the relations between Heat and other forms of Energy, and Mechanical Work, this thesis gives the results of, and is entitled "Researches in Thermodynamics."

An appreciation must be herewith expressed of the valuable teaching and aid of Professors Dirks and Reuling of the Mechanical Engineering Department, Professor Fields of the Drawing Department, Professor Ewing of the Chemistry Department, and many others who have assisted in the preparation of this work.

--E.E.E.

Big Rapids, Michigan.

June, 1928

9C059

CHAPTER I

THE TRANSFORMATION OF HEAT ENERGY INTO MECHANICAL WORK, AND VICE VERSA

Energy, which is defined in Physics as the power to do work, has several forms, including heat energy, mechanical energy, electrical energy, chemical energy, etc. We are here concerned with only the mechanical and heat forms of energy, neglecting the other forms in which energy appears except as is necessary for illustrating, aiding in, or bringing about, the transformation of heat energy into work, and mechanical work into heat.

Work equals force x space.
" " force per unit area x area x distance.
" " unit pressure x area x depth.
" " pressure x volume.

Thus we have work, or applied energy, as the product of two factors; one an intensity factor, force or pressure; and the other a distribution factor, distance or volume. So practically all forms of energy may be resolved into two factors, one of intensity and one of distribution. For instance, electrical energy may be considered, and graphically represented, as the product of voltage, the intensity factor, and ampere hours, the distribution factor. Heat energy may be thus represented as the product of an intensity factor, temperature, and a distribution factor, which is known as entropy. Entropy was formerly called the thermodynamic factor, but the shorter appellation "entropy,"

from a Greek word meaning unknown or mystery, was applied to it and the name is now generally accepted.

There is a definite relationship between heat energy and mechanical work, this relation being that 1 British thermal unit of heat equals practically 778 foot-pounds of mechanical work. Corresponding to the law of conservation of matter is the law of conservation of energy which states that the quantity of energy in the universe is fixed. The thermodynamic expression of this fact is that heat energy may be transformed into work energy, and vice versa; in other words, that no energy is ever destroyed, its form is simply changed. This is the first law of thermodynamics, which is expressed in symbols by the equation:

$$JQ \text{ equals } U_2 - U_1 \text{ plus } W,$$

or, in words, the quantity of heat added to a system goes to increasing the internal energy of the system or to doing external work.

It will be noticed, however, that this last statement and equation did not state that all the heat added to a system went to do mechanical work. The statement of this fact is the second law of thermodynamics, that energy tends always to change to a degraded form, that there is a degradation as well as a conservation of energy. Work energy is high-grade energy, electrical and similar energies are likewise high-grade, but heat energy is low grade; consequently, work or electrical energy may all be transformed into heat, but not all the heat in a system may be transformed into work. A proportion of the heat remains heat, as unavailable heat energy.

The efficiency of any transformation of heat into work depends, of course, on this remainder of unchanged energy. As the work done can be shown by an area on the Force-Space or Pressure-Volume planes, so the heat transformed into work may be represented graphically on the Temperature-Entropy plane; and, if the plane is extended far enough to show the amount of heat available to the system studied, the proportion of heat transformed into work to heat supplied to the system--in other words, the thermal efficiency--may be shown.

The transformation of heat energy into mechanical work requires a medium by which the transformation may be brought about, which medium is called the working medium and may be any substance which is affected as regards dimensions by the addition or subtraction of heat; and a mechanical contrivance, as well, is required to assist in, and make use of, the transformation, which mechanical contrivance belongs to the class of heat engines. These have almost unnumbered forms, and but a few of the possible forms at that, have been constructed. There are practically no devices made to produce heat from work for the sake of the heat produced, although all forms of brakes and friction involve a transformation of work energy into another form, usually heat; but devices, called refrigerating machines, are used where work is used to extract heat from a system, or rather the work assists in the process of heat extraction.

- - - - - - - - - - -

Working mediums, as stated before, may be anything having a dimensional change with the addition or subtraction of heat. First considering solid substances, as for instance the common metals, with definite coefficients of expansion with temperature changes, it is quite evident that a steel object with its hard surface resistant to pressure will do work if it expands against pressure with the addition of heat. By giving the metal object a certain shape and a mechanical contrivance to assist it, a larger proportion of work than the proportion secured from the simpler form of solid-expansion engine, may be got from the expansion of the metal. Of course, some solid substances shrink with increase of heat--at least between certain temperature limits; but it is not difficult to see how this property can be utilized in a heat engine as well as the expansion of the other substances.

It is, of course, perfectly possible to have a heat engine operating by the expansion of liquids as liquids, but the efficiencies to be obtained from most liquids are not such as would encourage the building of such engines, even just for laboratory specimens.

When we pass from liquids to vapors, however, we enter the field of great thermodynamic usefulness. The ability of vapors to expand with added heat against high pressures makes them valuable for the transformation of heat into work. Vapors are formed from the liquid state, usually, and do not approach the condition of perfect gases ordinarily until well beyond the vaporization point. One trouble with vapors is that those most used and most available require the addition of a great amount of heat to the liquid before the substance is completely vaporized. This heat is practically all unavailable below the amount needed to vaporize the liquid at the lowest pressure applied in the heat engine. The efficiency of the transformation may be and is being increased by raising the pressure limits under which the heat engine operates.

Water vapor (steam) and mercury vapor are the most common vapors in use; and, of the two, water vapor is by far the more used, having the advantage over other vapors on both commercial and available grounds.

A mixture of vapor and liquid is called wet saturated vapor; the temperature remains constant with constant pressure until enough heat has been added to vaporize all the liquid present, when dry saturated vapor is secured. Further heating at constant pressure raises the temperature and produces a superheated vapor. Of course, the entropy increases with all these additions of heat. The peculiarity of a vapor is that its pressure, volume, and temperature are not mutually fixed and interdependent as with gases; but that the quality--per cent by weight of vapor in the mixture of liquid and vapor--in saturated vapors, or the degree of superheat--number of degrees on the temperature scale above the vaporization temperature corresponding to the pressure--of superheated vapors must also be taken into account. These peculiarities of vapors have made large sets of tables and complicated charts showing the relations between the quantity of heat that has been added to the vapor above a certain point--usually the condition of the liquid at a temperature of 32 degrees Fahrenheit and zero pressure--, the entropy change above that point, the pressure, the temperature, the density and conversely the volume per unit mass, etc. necessary to avoid repetition of difficult experiments and the use of cumbersome computations.

Gases are likewise very valuable and much used in heat engines. In the use of gases, there are two methods depending on whether the gas is combustible or not. Air and other non-combustible gases must be heated from an outside source. Combustible gases are heated by their own combustion. Gases may exist as gases before introduction into the heat engine or may be formed from vaporized liquid upon entrance into the engine.

A perfect gas, that is a perfectly elastic gas, which does not exist in fact but which is very closely approximated by air and other common gases, follows the law that the product of the pressure times the volume equals the weight times a constant times the absolute temperature; expressed symbolically this becomes the equation:

PV equals MBT.

Where P equals pressure in pounds per square foot,

V " volume in square feet,

M " the molecular weight in pounds,

and T " the absolute temperature in degrees Fahrenheit,

the constant B equals 1544 for all gases. From this the value of B for any given weight of gas may be computed. Air, while not a compound, may be assigned a molecular weight by taking air as a mixture of 77 parts by volume of nitrogen, N_2, with a molecular weight of 28 and 23 parts of Oxygen, O_2, molecular weight 32, and finding the average molecular weight of the mixture. This gives

77 x 28	equals	2156
23 x 32	"	736
100 x average molecular weight	"	2892
Molecular weight of air	"	28.92

Value of B for air where M equals 1 pound equals 1544 divided by 28.92 equals 53.4. The same procedure may be followed in other cases.

From the above statements it is evident that the determination of any two of the three conditions or qualities, pressure, volume, and temperature, governing a gas decides the third condition or quality; that is, the pressure is dependent only on the volume and temperature for a given weight, and so on. Other ways of stating the same thing are Boyle's Law, "If the temperature is kept constant, the volume of a given weight of gas varies inversely as the pressure," and Charles' Law, "The increase of pressure when the gas is heated at constant volume is proportional to the increase of temperature." Expressed by symbols Boyle's Law becomes:

$$PV \text{ equals } C, \text{ or}$$

$$P_1V_1 \text{ equals } P_2V_2 \quad " \quad P_3V_3 \text{ equals} - - -.$$

and Charles' Law is:

$$P - P_0 \text{ equals } K(T - T_0).$$

Charles' Law plotted on rectangular graph paper indicates that there is a point at which the pressure becomes zero when the temperature reaches said point, and this locates the absolute zero of temperature, or zero on the gas scale, which zero is 460 degrees below zero Fahrenheit; so that 460 degrees must be added to the Fahrenheit readings to obtain absolute temperatures or temperatures on the gas scale. This leads to still another form of the statement

of the relation between the three coordinates defining the state of a gas, that is, that expressed as an equation,

$\frac{PV}{T}$ equals K, or $\frac{PV}{T}$ equals $\frac{P'V'}{T'}$.

Where but one unit of weight of gas is considered, it may be seen that this is the same as

PV equals BT, B equaling the constant K,

or for M units of weight, we again reach the expression

PV equals MBT.

Gases are rather seldom simple compounds, but are usually mixtures in which the relations between the pressure, volume, and temperature must be determined by methods similar to that used in figuring out the value of B for air. That is, the average quality, whether it be molecular weight, specific heat, density, or what not, must be taken from the proportions of the various compounds or elements present in the gaseous mixture; and computations are then made using this average quality. Whether the quality refers to volume, as in the case of molecular weights, or to weight, as in the case of specific heats, determines whether the proportions of the constituent compounds are to be taken by volume or by weight.

In computations dealing with the products of the combustion of combustible gases, the question of mixtures looms large; for there is, besides the compounds of oxygen with carbon, hydrogen, sulphur, etc., the nitrogen of the atmosphere that is admitted with the oxygen required for combustion and

also in most cases an excess of air of from 10 to 100% necessary to insure complete oxidation.

One difficulty with combustible gases used in heat engines has been that the temperatures produced have been so high that the metal of the mechanical device has been weakened or destroyed by the heat unless means were taken to carry away some of the heat, which was thereby rendered useless for producing work. The best metal now produced can not stand constant exposure to the high temperatures of the uncooled combustible-gas heat engine.

However, the maximum temperatures obtainable from gaseous combustion have not been as high as were originally calculated from the heats of combustion of the different gases and elements, determined experimentally by various kinds of calorimetry. This is because in making these original calculations it was assumed that:

> The specific heats of the gases evolved remained constant, whereas they increase greatly in value with high temperatures.
>
> No heat was supposed to be lost during the combustion process, whereas, in reality a great deal of heat energy is lost by radiation and conduction during combustion.
>
> The process of combustion was carried to completion; while, in fact, especially at high temperatures, there is dissociation of the products of combustion back into the original elements or compounds, or into others.

The first two false assumptions were strictly thermodynamic errors; but chemistry had an important part to play in correcting the third. In any chemical reaction--and combustion is, of course, and essentially, a chemical reaction--there is an action proceeding each way, but with most reactions at ordinary pressures and temperatures the force driving one phase or action is insignificant compared to the force driving the opposite action, and the reaction goes to practical completion in the direction of the overwhelmingly larger driving force. But the relations between these driving forces change with the temperature so that a point or temperature is reached where the opposing forces just balance each other; and the reaction halts. A condition of chemical equilibrium has been established and complete combustion is prevented. This condition of equilibrium is determined by the partial pressures of each of the substances in the mixture at the time of reaching the equilibrium. For instance in the combustion of carbon monoxide, CO, to form CO_2, a constant K_p equals $\frac{P'CO_2}{(P'CO)(P'O_2)^{\frac{1}{2}}}$, called the equilibrium constant, represents the product of the partial pressures of the products of reaction divided by the product of the partial pressures of the reacting substances, each partial pressure having an exponent equal to the coefficient applied to the substance to which the partial pressure relates, the equation for the reaction mentioned being: CO plus $\frac{1}{2}O_2$ equals CO_2. This is the same as the chemical equilibrium obtained in a solution when the

concentrations of the resultant compounds divided by the concentrations of the reacting compounds equals a constant K. The Law of Mass Action to the effect that the speed or rate of any chemical change is proportional to the active mass, that is, the molecular concentration of each substance engaged in the reaction, which holds for all chemical reactions, whether reversible or not, is the basic statement from which those relating to the equilibrium constant are derived. The values of K and K_p are always constant at a given pressure and temperature when the condition of equilibrium is reached. By very lengthy equations involving the heats of combustion, the intrinsic energies, and the thermal potentials above the standard conditions of 32 degrees F. and atmospheric pressure, Goodenough and Felbeck arrive at a relation between the values of K_p, for each of several combustion processes, and the temperature. Having this, the direction in which the reaction will progress at any given temperature can be determined; and the temperature at which the state of equilibrium is reached may be calculated. This is theoretically the maximum temperature attainable, and may be reached with rich mixtures of fuel and air and rapid combustion; but can hardly be obtained with thin mixtures and slow burning.

To boost this maximum temperature and with it the pressure and thermal efficiency--at least, theoretically to boost the efficiency--a means must be found of keeping down the concentration of the products of combustion, thereby

causing the reaction to proceed further towards completion in an attempt to maintain the value of the constant K_p at the point it attains at equilibrium. In gaseous combustion this means decreasing the partial pressure of the product of combustion. This can be done by adding some element or compound that will combine with the products of combustion in such a manner as to prevent the reaction from proceeding backwards. That is, the new compounds formed must have no tendency to return to the original states, or at least must have a much slighter tendency to revert than the common products of combustion.

Mixtures of gas and vapor, such as atmospheric air, damp gas, etc. furnish problems combining the features of both vapor problems and gas problems; and such mixtures are becoming increasingly important with the adoption of the system of keeping the temperature down in gas engines by spraying water in with the hot gases. In the case of the atmosphere, the amount of water vapor is so small, comparatively, that it may be neglected in ordinary heat engine computations; although it must be figured on quite closely in problems concerning heating and ventilation, where relative humidity is important. For close work, the temperature of the air must be taken, and then a reading taken of the temperature of a wick soaked in water and circulated freely in the air. An instrument called the sling psychrometer is made to take both these temperatures simultaneously, and from this pair of temperatures, the relative

humidity may be found by reference to charts which have been formulated, or by the use of Carrier's Formula:

$$e \text{ equals } e' - \frac{(P - e')\,(t - t')}{2755 - 1.28t'}, \text{ where}$$

t equals dry-bulb temperature in degrees F

t' " wet-bulb temperature in degrees F

e' " vapor pressure in #/o" corresponding to t'

e " vapor pressure in #/o" corresponding to t_o, the dew point, and

P equals barometric pressure in pounds per sq. in.

The steam in the air is always dry saturated or superheated except when actual condensation in the form of rain, mist, dew, etc. is occurring, for at the low partial pressure of the water vapor in the atmosphere, the boiling point, or perhaps more correctly stated, the vaporization point is below ordinary temperatures. When the vapor pressure rises with an excess of moisture, or the temperature of the air falls below the vaporization point, part of the water in the air condenses as one of familiar forms of rain, snow, etc. The wet-bulb temperature never falls quite to the dew point, however, if the air is at all above saturation temperature due to conduction of heat away from the cold bulb by the warmer air.

The proportions of gas and vapor in a mixture are made manifest through partial pressures. Dalton's Law, that the pressure of the mixture is the sum of the pressures of the constituents, gives a basis for comparing pressures; and, if an idea can be obtained of the degree of superheat,

or the quality, of the vapor or of the composition of the gas, the remaining weights, volumes, or proportions may be secured easily. Should the exact composition or qualities not be obtainable, an estimate of partial pressures may be made from the weight of the constituents and the mixtures. By the use, then, of gas constants for the ingredients and the mixture as a whole, accurate enough results may be obtained for ordinary heat-engine work involving gas-vapor mixtures.

- - - - - - - - - - - -

The Thermal Efficiency of Heat Engines for any and all working mediums is limited to that of what is called the Carnot Cycle, which is expansion at constant temperature, further expansion at constant entropy, compression at constant temperature, and compression at constant entropy back to the starting point. Many proofs are given that there can be no cycle of greater thermal efficiency than this one, but one of the simplest and most sufficient is that furnished by the temperature-entropy diagram, on which the cycle named is a rectangle bounded on top and bottom by constant temperature lines and on the sides by constant entropy lines. The area beneath this rectangle is unavailable energy. Since a rectangle possesses the maximum volume possible between two straight parallel lines, it is plainly seen that the Carnot cycle represents the most heat converted into work between any two given temperatures or between any two given entropies.

Likewise it can be seen upon further investigation of the diagram that this represents the most heat put into the system, represented by the area under the upper constant temperature line, and the largest proportion of that taken out between the temperatures fixed by the operating conditions; therefore the Carnot cycle is the most efficient thermally, between any given temperature limits, of all possible cycles.

The point of absolute zero entropy evidently lies at negative infinity as far as regards the range of temperatures with which we have to deal; so, entropy having an infinitely large value at any point we have occasion to consider in heat engine operation and design, we select for it an arbitrary starting point, usually the liquid line of water at zero pressure and 32 degrees F. The energy head or thermal potential of a working substance, representing the energy in work and heat required to bring it (the working substance) to a given point or condition is likewise taken from an arbitrary zero, at 32 degrees F. and zero or atmospheric pressure usually. This is represented by the symbol i, while entropy is variously represented by ϕ, N, or S, the latter of which will be used here. Expanding gases have different specific heats, also, according to the line they follow in expansion, while there is another specific heat for the increase of temperature without expansion. For gases whose molecules consist of single atoms the ratio between the specific heat at constant pressure and that at constant volume, C_p/C_v, equals 1 2/3 or 1.67; for diatomic gases it is approximately 1 2/5 or 1.40; and for

triatomic gases it is about 1 2/7 or 1.28. For air, for instance, which is a mixture of two diatomic gases, oxygen and nitrogen, C_p equals .242, and C_v equals .173, and .242/.173 equals 1.40 approximately, although of course the values of the specific heats vary slightly with the temperatures. Other terms used in connection with working mediums are: change in intrinsic energy, $V_2 - V_1$, which relates to the energy which the medium has stored within it; external work, which represents the work, W, done on or by the substance in reaching a certain state or condition from another state or condition; and quantity of heat added or abstracted, Q if measured in B.t.u. or JQ if considered as foot-pounds, which is practically equal to the thermal potential i when both are considered above the same zero, except that i includes the work energy necessary to put the working medium into the heat engine equipment and Q includes only the heat and other energy added to it after it (the working substance) gets into the heat engine equipment. There are other coefficients connected with the working mediums, such as the amount of heat required to raise the pressure one unit at constant volume and again at constant temperature, etc.; but problems necessitating the use of such constants are more rare than those requiring C_p and C_v and K equals C_p/C_v : so they are not discussed further here, except to say that such problems are probably more readily solved from the tables or charts than from the use of constants which vary widely as other conditions vary.

The first practicable heat engine made use of water-vapor or steam as the working medium, and steam still does

more work than all other working substances together that are used in mechanical heat engines. The great drawback to steam has been that mentioned in connection with vapors as working mediums, namely, the tremendous heat of evaporation required to change the small volume of liquid (water) to the large volume of vapor (steam). This is being escaped from in the upper pressure ranges by running near the critical temperature and pressure at which the change from water to steam is accomplished with zero heat of evaporation. On the other end of the pressure scale, the back pressures and temperatures are being reduced to as low a value as practicable by means of condensers, etc.; but, even at low pressures, there is a great deal of heat of evaporation left in the steam which is rendered unavailable. The reciprocating steam-engine to allow complete expansion of the steam would have to be of such tremendous size and run with such great speed, with consequent large floor space and cost and maximum vibration, that the remedy is sought in the turbine, which is intrinsically less efficient than the engine, because of having to make two changes in the form of the heat energy of the steam--heat or pressure energy to kinetic energy in the steam and from that to mechanical work on the turbine blades--instead of just the transformation from heat energy to work, as in the piston engine. To get around the disadvantages of both, a rotary engine has been long sought for, over 2200 patents having been granted in the United States on inventions relating to rotary engines; but the foe of efficiency and economy in these engines has been excessive leakage, which no one has yet been able to get around. If this trouble can

be overcome, there seems to be considerable of an opening for this type of heat engine.

Gas engines suffer most from excessive heating, the combustion temperatures rising beyond the strength limit of the metals available unless cooling is carried on with loss of heat and otherwise available energy by the cooling medium; that is, available energy is rendered unavailable by being carried away in the cooling substance. At that, gas engines show the highest efficiencies of any heat engines at the present time.

The type of gas engine now used is the internal combustion class, the old "hot-air" and similar gas engines operating on a medium heated by outside heat having to give way before the higher efficiencies and greater power for the size and weight, of the engines operating on a medium expanding due to the heat of its own combustion.

In America, the gas turbine is yet regarded as purely a theoretical possibility; but in Germany, Hans Holzworth, chief engineer of Thyssen and Company, of Mulheim, has designed at least three practical gas and oil turbines and is working on a fourth, one of 10,000 K.W. capacity at 1500 r.p.m. The thermal efficiency he obtains is low, compared to gas engines and good steam installations; but the cost of the plant, the maintenance, and operating charges are so low as compared with the other styles of installations that the commercial efficiency is yet higher than steam turbines or steam or gas engines, in spite of the higher thermal efficiencies of the latter.

CHAPTER II,
QUESTIONS AND ANSWERS ON GAS TURBINES

The discussion of Gas Turbines being really a discussion of the questions that may arise concerning their economy, efficiency, and practicability, in this report of findings, said findings are given as the answers to a tabulated list of questions concerning the various features of design, operation, and efficiency of gas turbines.

First are given a list of questions (and the findings thereon) concerning which is the better of two, three, or more choices of design or method of operation; then there is the summation question as to whether or not the operation of gas turbines pays under the most favorable general conditions, and the findings in answer to that question and giving the conclusions to be drawn.

The questions are numbered in order and each one is fully stated before the report of findings is made; so there is no doubt as to the matter being investigated and discussed.

Question I.

Which is the better?

1. Explosion type turbines with consequent change in the velocity of the impinging gases and hence lowered blade efficiency, or

2. Constant-pressure type turbines with high and constant temperature requiring either the addition of cooling gas or vapor, pre-cooling of the gases, or special materials in the turbine parts?

Answer

While the majority of designers prefer the constant-

pressure type, the most successful installations existing at present, those designed by Hans Holzworth, chief engineer of Thyssen & Company, Mulheim, Germany, are of the explosion type.

The explosion type calls for a large amount of negative work in cooling and scavenging the combustion chamber, but the constant-pressure turbine demands likewise considerable negative work in forcing the air and fuel into the chamber against the high pressure necessary to satisfactory combustion. Of course, in the explosion-type the charge must be compressed, too; but the compression takes place before the explosion and therefore at a lower pressure than combustion pressure.

The explosion-type offers as its chief advantage its use of the gases without the great immediate dilution with a cooling medium common to most constant-pressure turbines; although the explosion-type has cooling and scavenging fluid put through its chamber between explosions. A high proportion of the energy in the exploded gas is then absorbed by the turbine rotors; and, since the jet of high temperature gas impinges on the blades for but a small fraction of the time, the blading does not become heated to a dangerous degree as it would in a constant-pressure high-temperature jet. The disadvantages of the explosion type are the variation in the velocity of the discharged gases, making it necessary to fall short of maximum absorption of the kinetic energy of the jet except for very short periods just after each explosion; the mechanical difficulties in getting the chamber

charged and ignited at just the proper time; the vibratory effect; and the amount of negative work necessary to scavenge and cool the chambers between explosions. Difficulty has been experienced in getting the explosion at just the right time, the ignition occasionally being delayed by causes not yet thoroughly understood, resulting in a heavy explosion and improper combustion, emission of smoke, etc. Holzworth's turbines, however, have not shown much tendency towards this defect of function; and he seems to have pretty nearly overcome the difficulty.

The big advantage of the constant-pressure type, of course, lies in the constant pressure and hence constant velocity of the jet allowing the blading to be so designed as to secure the maximum absorption of the kinetic energy of the gas stream. Theoretically, the constant high temperature should offer the advantage of high thermal efficiency, according to the formula:

$$\text{Effy. equals } \frac{T_1 - T_2}{T_1},$$

but the temperature of the undiluted product of combustion, sometimes above 3000 degrees F., is too high for constant play upon any blading metal which is really suitable and economical. Quartz has been used, but is brittle and expensive; and no available metals retain any strength even should they retain their form at such high temperatures. From this fact arises one of the disadvantages of the constant-pressure turbine, the necessity for cooling the product of combustion before it can be used, thereby reducing the temperature range and thermal efficiency under which the

machine operates. Other disadvantages are the amount of negative work required to charge the combustion chamber against the combustion pressure; the amount of negative work required to add the cooling fluid--if one is used--against combustion pressure; the loss of heat energy by radiation if the discharged gases from the chamber are surface cooled; and the loss of expansive power in the addition of a non-combustible diluent.

It will be seen that both types have their disadvantages, and plenty of them. In an attempt to escape as many of these drawbacks as possible, turbines that are rather combinations of the two types have been designed. One operates on the principle of the gas first expanding on explosion, and then contracting due to the union of the hydrogen in the gas with the oxygen in the air to form water. This contraction produces a vacuum which draws a fresh charge into the chamber which is still hot enough to ignite the gas. Explosions occur at the rate of 3500 to 5000 per minute, giving practically continuous flow, but the turbine as at present designed operates without compression, and hence its combustion efficiency is low. But plenty of data is on hand for work upon the gas turbine as regards chemical, thermal, and thermodynamic possibilities, and only mechanical obstacles appear in the way of the devising of a turbine with a maximum of the advantages of both the explosion and the constant-pressure types and a minimum of their disadvantages. Such a turbine probably will combine also the structural details of both types.

Question II.

Which is better?

1. To attempt to use the high temperatures of richly-mixed fuel to secure a high thermal efficiency by the employment of heat-resisting casings and bladings, without any cooling of the products of combustion other than by doing mechanical work,

2. To attempt to use the high temperatures of the fired gas and air to expand cooling gas or vapor (air or steam) mixed with the products of combustion and make this expanded cooling material assist in the mechanical work of the products of combustion by adding to the volume of said products in the direct mixture, or

3. To attempt to make the cooling gas or vapor--after surface-cooling the fired gas--do work in an auxiliary to the main unit that is operated by the combustion products?

Answer.

It is almost out of the question to attempt to build the casing and blading of materials that can withstand a continuous blast of gas burned with little or no excess air. Such materials as would withstand temperatures so high either lack the requisite strength for parts of such a hard-worked engine as a turbine or cost too much, or have both these disadvantages.

The other two methods of operation have much its advantages and disadvantages, and both have been used in gas turbines that have functioned with more or less success. Of course, if one wishes to look at it that way, an explosion

type turbine is really one employing a diluent, the scavenging air, sometimes mixed with steam, to reduce the mean temperature of the combustion products; only in the explosion type the exit velocity varies, as does the pressure and the composition of the discharging fluids from the combustion chamber.

The use of a direct mixture of diluent and combustion products necessitates a greatly increased amount of negative work to put the increased quantity of fluid into the chamber, unless water is sprayed in from a nozzle or atomizer while still in liquid form, in which case there is the resultant high loss due to the latent heat of vaporization of water. Unless the turbine is fitted with an exhauster or other device for reducing the pressure below atmospheric on the exhaust, the pressure range is much reduced, and the thermal efficiency is greatly lessened. The use of the direct mixture in a constant-pressure turbine is, however, probably the simplest form of gas turbine capable of practical operation.

An auxiliary unit, operated by surface radiated and conducted heat from the main gas turbine combustion chamber, in effect just another turbine, operating with a working fluid heated by external means; and this auxiliary unit is subject to the same laws as any simple turbine of the type to which it belongs. So this unit usually is an ordinary steam turbine of a type and design best suited to conditions imposed by the location, size desired, and other factors not particularly affected by the main unit itself. The chief objection to this auxiliary unit to the gas turbine

is that it at least doubles the complication of the engine; and, if it is a steam unit expected to operate at near maximum efficiency--and a steam unit, of course, has advantages here as elsewhere over hot-air engines, mercury turbines, etc.--, a condenser and other equipment must be added which will increase the space required and the complicated nature of the mechanism considerably. This naturally obviates the consideration of this system as applied to any but large units.

Question III.

Which is better?

1. The doing of a large amount of negative work before combustion by high compression before admission of the fuel and air to the combustion chamber,

2. Admission of air and fuel at low pressures, and operation by the power unit at low pressures, or

3. Admission of air and fuel at low pressures into chambers where it can be heated to higher pressures by the heat of combustion in adjacent chambers, by regeneration from the hot exhaust gases, or by coming into contact with hot fired gases just before combustion?

Answer.

Neither in theory nor in practice has low-pressure combustion proved efficient. Combustion is poor, and the thermal efficiency is low. High--from 35 to 600 pounds per sq. in., depending on the fuel, etc.--pressures must be obtained in some manner; and the simplest way is by compressing the gas and air to the desired pressure before

admitting it to the combustion chamber, although this necessitates the doing of a large amount of negative work. In cases where the turbine and compressor efficiencies are both low, and a high compression pressure compared to the mean explosion pressure is required, the amount of negative work may equal or exceed the amount of positive work, and the turbine produce no work, or even require extra work to enable it to operate.

The mechanical difficulties necessary to obtain quick heating of air compressed to a medium pressure, by surface contact with the walls of the adjoining combustion chamber, would be great, as they would obtain the heating from the exhaust gases or from direct contact with fired gas without seriously decreasing the pressure of the freshly-fired gas. By a suitable arrangement of chambers and valves, the arrangements could be made for heating in any one of the manners suggested; but the greater problems arise in obtaining the heat interchange in the short time necessary in order to keep up the supply of combustibles, and in doing this without affecting too much the pressure in the combustion chambers. Whether the cost and complication of the extra mechanical equipment required for this raising the entrance pressure by preheating after medium compression would be repaid in the increased efficiency over a simple compressor is a problem that would have to be solved by direct, painstaking, and well-continued experiment.

Question IV.

Which is better?

1. The use of exhaust gases emerging around atmospheric

pressures to heat gas or vapor (air or steam) for running auxiliaries,

2. The use of exhaust gases emerging at atmospheric pressure to heat incoming air and fuel to produce higher pressure and better combustion, or

3. The use of an exhauster or some other device for in some way reducing the back pressure below atmospheric and thereby getting greater temperature range and expansion and more power from the products of combustion?

Answer.

All three of these systems have been used in practice with more or less success. A steam turbine run from steam heated by exhaust gases may, under favorable efficiencies of turbine and compressor and low ratios of negative to positive work, generate enough power to run the compressor.

Regenerative heating or pressure-raising by means of the exhaust gases gives about the same added efficiency as the use of an exhaust heated steam-driven auxiliary; and may, in most cases, require a less complicated mechanism. On an explosion type turbine, though, the use of the auxiliary may be preferable to heating regeneratively, when there is a cooling blast of air or steam to be passed through the same path as the fuel mixture travels, as in that case the heat is wasted on the cooling fluid and the efficiency of the cooling material is decreased accordingly.

An exhauster, usually, consumes as much power as it adds, unless the gas is cooled by being used for regeneration before passing through the exhauster, in which case its lessened volume permits of the exhauster doing less work

than is done by the greater expansion of the gas in the turbine. The exhauster and regenerator, then, combined in the manner described, work well together in increasing power and efficiency. The exhauster and auxiliary do not work very well together, however, as the auxiliary makes the function of the exhauster merely that of a pump for the fluid heating the steam or other working medium of the auxiliary, and any method of inducing a flow of the exhaust gases over the boiler will do practically as well as an exhauster, without requiring probably as large an expenditure of negative work. There is not usually heat enough left in the exhaust gases after regeneration to satisfactorily operate an auxiliary power unit.

Since the gases found in the exhaust of a gas turbine or engine do not liquefy until nearly at a temperature of absolute zero, they are not capable of being condensed for practical purposes; and therefore a condenser analogous to a steam condenser can not be used on a gas turbine. To actually condense (liquefy) a very small portion of the exhaust gas of a gas engine or turbine would require cumbersome apparatus and an outlay of money that would make the power cost prohibitive. The only practicable form of pressure reducer at present apparent is the cooler and exhauster type mentioned before in the discussion of regeneration.

Question V.

Which is better?

1. Large units, necessarily stationary or marine, developing

power for factories, lighting plants, ship-propulsion, etc., or 2. Small units, which may be portable or tractice, developing power for automobiles and small portable power applications?

Answer.

Large units--300 H.P. and up, especially up to 5,000-10,000 kilowatts--are found to be the only practicable units at present; although, of course, the laboratory machines of Zoelly, Warner, and others are made in smaller sizes. But when results are desired on a dollars and cents basis, the little laboratory machine is found impracticable. Some smaller units, comparatively smaller, are installed on torpedo boats, etc. On airplanes intended for flying at high altitudes, the exhaust from the regular piston and crank gas engine is used to drive a gas turbine running the supercharger. Torpedoes are also sometimes equipped with small, very high-speed gas turbines, operating at constant pressure as the result of the combustion of compressed air and fuel. But the object of using a turbine in large gas installations is to cut down the tremendous size as much as possible, which would not be done by making the turbine merely an auxiliary to the main unit, as it is on the airplane engine. While another use could be found for the power besides running a supercharger--running a compressor for instance, which corresponds at atmospheric pressure to a supercharger at the pressure found five miles above sea level--the exhaust from the main unit would have to be just so much higher to allow a turbine to operate with atmospheric exhaust; and there would be more likely a loss instead of a

gain in efficiency through taking the power out of the gas in two engines rather than one, and there certainly would be an increase in cost. The airplane engine, designed to operate with varying back pressures, could dispense with the turbine at atmospheric pressure and use it with advantage at high altitudes; but an engine operating at a constant back pressure would have no use for such an auxiliary unit. The aviation motors, anyway, are designed more for maximum H.P. per unit of weight than for economy or thermal efficiency; which case is directly opposite that of the large gas power unit. Likewise the torpedo motor makes but one run in its brief career before it is blown up, and high economy and thermal efficiency and long life to the casing and bladings are of little consequence as long as it has the speed and power to direct its charge fast, far, and accurately while it lasts.

The application of the turbine principle to the small gas motor, such as the automobile engine or the portable farm engine, faces such competition that it seems unlikely to be brought about for many, many years, if at all. The small plant is a very efficient developer of power for its size; and the small turbine, like the small steam turbine compared to the small reciprocating engine, is at a disadvantage. The auxiliaries, such as compressor, regenerator, etc., required by a gas turbine make it too complicated and cumbersome to compete with the reciprocating gas engine, especially since the advantage in thermal efficiency is with the reciprocating engine.

Question VI.

Which is better?

1. The impulse type of gas turbine with all the energy removed in one or two velocity stages,

2. The reaction type with a slight pressure drop per stage and many stages, or

3. Some combination of the two, as is sometimes used in steam turbine design?

Answer.

All practical gas turbines at present used or designed, from the little high-speed torpedo motor to the 10,000 kilowatt Holzworth turbine now being built in Germany, are of the impulse type with usually two velocity stages. The impulse type takes the energy out of the gas quickly before the blading gets hot; and, with two velocity stages, keeps the peripheral velocity down within safe limits. With the reaction type, the first sets of blades and nozzles are exposed to intense heat; and the gas has to be throttled down or otherwise reduced in velocity because of the lower peripheral speed of the rotor. Therostically, the reaction type with cooled gas should operate just as efficiently as the impulse type, but practical designers, such as Holzworth, Arinengaud and Lemale, and Pelterie, find that the impulse turbine suits them best.

Question VII,

Which is better?

1. A fuel already in the gaseous form,

2. A form of easily volatilized liquid fuel, such as gasoline, naphtha, benzene, kerosene, etc., or

3. A fuel in the form of heavy oils volatilizing only at high temperatures, such as fuel oil, etc.?

Answer.

The choice of fuel depends largely on the locality, relative cheapness, etc.; but gas turbines work best on fuels suited to their particular types. Holzwarth's large turbines operate on natural or producer gas--although his 300 K.W. unit operated on fuel oil--, Warren demonstrated the chamber and nozzle efficiency of gasoline used in a small unit, and in between these extremes are many designers whose turbines operate, or are supposed to operate on fuel oil, gasoline, kerosene, etc. It seems that the gas turbine uses best about the same kind of fuel as does a reciprocating gas engine of equal power and corresponding size; gasoline, benzine, kerosene, etc. for the smaller sizes; and fuel oil, natural gas and producer gas for the larger units.

Question VIII.

Which is better?

1. Both carburetion and vaporization of the fuel before it enters the combustion chamber,

2. Carburetion outside and vaporization inside the combustion chamber, or

3. Both carburetion and vaporization within the combustion chamber?

Answer.

Carburetion and vaporization of the fuel, complete mixing with air and preheating to a gaseous state if liquid fuel is used, should both be accomplished before the mixture is ignited to secure maximum results as regards combustion; and

the point where this complete carburetion is secured or should be reached, depends on the type of turbine and the nature of fuel used. With gaseous fuel there is, of course, no further vaporization required, and the mixing of the gas and air is all there is to look after. This should be accomplished before ignition. In any explosion type turbine it can be accomplished just as well within the chamber before ignition as not. In a constant-pressure turbine, the mixture should take place in the nozzle or injecting apparatus, so that, as the gas issues at the point of ignition, it would be thoroughly mixed ready to burn perfectly.

Liquid fuels should be both carburetted and vaporized before ignition. If the turbine is of the explosion type, this may be done quite readily in the combustion chamber, or if the flow is such in a constant pressure type that combustion occurs only at the far end, giving the gas and air a chance to become thoroughly vaporized before ignition. But, with liquid fuels in a constant-pressure turbine, it is probably best to have the carburetion take place before the air and fuels get into the combustion chamber. They can then be volatilized as they enter and be ignited immediately upon entering. Liquids occupying less volume than gases, there is less negative work to be done, if the fuel is made to enter the combustion chamber against a given pressure in a liquid rather than in a gaseous state. But unless vaporization is complete, this gain in power is more than offset by the loss due to incomplete combustion.

Question IX.

What are the comparative thermal efficiencies and commercial efficiencies of gas turbines, gas engines, and steam turbines on power installations?

Answer

The thermal efficiency of the best gas turbine is about equal to that of the best steam turbine and much inferior to that of a reciprocating gas engine of the same power. There is little analogy between steam and gas turbines. Steam turbines owe their superiority in economy and efficiency over recip rocating engines to their ability to make use of greater expansions and lower vacuums than the engines, due to size limitations, can cover. Between the same conditions of temperature and pressure, steam turbines, especially in medium large sizes, are outclassed by piston steam engines. The turbine makes a double transformation of energy; from pressure energy to kinetic energy in the steam and from this kinetic energy of the steam to the mechanical energy of the rotor: while the engine makes but the one change directly from pressure energy to mechanical energy, and therefore has less chance of wasted energy being lost as heat during transformation from one form to another. The gas turbine, as well as the steam turbine is up against this fact, and is still a long ways from getting around it, as far as thermal efficiency is concerned.

In the smaller sizes the gas turbine, at present, has no chance at all against the gas or steam engine; but in the larger units other considerations besides thermal efficiency

have great weight. The gas turbine occupies much less space and weighs and costs much less than a reciprocating gas engine of equal power or than a steam turbine with all the equipment, boilers, condensers, feed-water pumps, etc. that are necessary to the operation of a modern steam plant, although the actual turbine is much smaller for steam than for gas. Also the operating cost is less for the gas turbine than for either of the other two.

Figuring cost of fuel, of operation, of interest on investment, of depreciation charges, of lubrication, etc. the large (Holzwarth) gas turbine costs roughly about half as much as a gas engine and about .6 as much as a steam turbine per unit of work (Kilowatt-hour) produced. So that, as far as what may be called "commercial" or dollars-and-cents efficiency is concerned, the gas turbine has the edge on its rivals.

Question X.

After assuming the most favorable individual conditions grouped together or the most favorable combination of individual conditions affecting gas turbine design, whichever will produce the maximum thermal and commercial efficiencies, is the gas turbine able to compete with the gas engine and steam turbine; and, if so, under what conditions and in what forms?

Answer.

As just pointed out, the Holzwarth turbine is able to hold its own against steam turbines and gas engines as

regards actual cost of power produced. It seems unlikely that the gas turbine will soon match in thermal efficiency the gas engine; and, with higher pressures being used and greater superheats and more nearly complete vacuums in steam installations, the gas turbine is going to be hard put to match the thermal efficiency of steam. So, should the price of fuel rise considerably, compared to the rental of floor space, the cost of manufacture, etc., the gas turbine would be rendered impractical; but this seems unlikely in the very near future.

The Holzwarth is an explosion-type turbine with the exhaust gases divided, part to do regenerative heating, and part to run steam-driven auxiliaries. Several experiments have been or are being made with constant-pressure type turbines, and when a blading has been devised that will stand high temperatures and certain other minor mechanical difficulties are overcome a constant-pressure turbine matching in efficiency the Holzwarth can be expected. Most theorists favor the constant-pressure type and are working on that kind of turbine, while Professor Rateau has found that tungsten tool-steel blading will stand temperatures up to 1200 degrees F.; so the day of the successful constant-pressure type seems near.

Chapter III.

As we follow the subject of thermodynamics up from the simpler and more obvious manifestations of the relation between heat and work as shown in Joule's Law in Elementary Physics, through the more and more complex forms of the mechanical application of this law and mechanical principles in Engineering Thermodynamics, to the highly technical and elaborately complicated and mathematical treatment of Thermochemistry, we see the subject broadening to take in the whole field of the sciences dealing with non-living matter and even to some extent entering into, and being entered into by, the biological sciences. Finally we reach the science or scientific study in which all the physical sciences are united, Physical Chemistry, in which first causes and primary manifestations are sought out. And, when we reach this study of basic physical characteristics and manifestations, we find that already a great many limits to the fundamental commonplace conceptions of space, time, and matter, and their relations with each other, have been proved, or postulated with a lack of proof of the contrary, by physicists, engineers, and chemists, in these comparatively elementary sciences and applications; and we also find that Physical Chemistry sets up further limits; and, finally, we may see where a comparison and correlation of these various facts and postulates will lead to still further limits being hypothesized, at the very least, in an attempt to get yet closer to fundamental truth.

To begin with ordinary Physics, we find the postulate of the Conservation of Matter sets a maximum limit to the

quantity of matter. "The amount of matter in space is fixed. Matter can be neither created nor destroyed." A corollary to this is the law of Conservation of Energy. "The total amount of energy in all creation is a constant. Energy can be neither created nor destroyed." A special application of the latter law is the doctrine of the Conservation of Electricity, "The quantity of Electricity in space is fixed. Electricity can be neither created nor destroyed." These postulates, of course, say nothing about the fact that matter, electricity, and energy in general, have varied and varying distributions and forms or manifestations. Taking this for granted, the postulates--or at least the first two--are accepted as laws in the light of lack of proof to any contrary, by engineers and physicists in general everywhere.

Physics, of course, does not go beyond the molecule in the direction of the infinitesimal, as the molecule is the smallest amount of any physical element or substance existing as such an element or substance; but it does tell us of an indivisible minimum unit of static electric charge, the value of which has been determined to be 4.774×10^{-10} Electrostatic Units. (An Electrostatic Units is that charge possessed by each of two poles one centimeter apart and repelling each other with a force of one dyne). The intensity factors in Physical functions, such as temperature in heat, pressure in work, and force in energy, are postulated as varying or variable from Absolute Zero to Infinity, except perhaps in the case of the temperature and pressure of very large masses of matter, such as some of the huge nebular

masses observed by astronomers in far-off space, in which the pressure that would be produced by the tremendous gravitational effect of the huge quantity of matter may be limited by the extreme molecular activity or heat produced towards and in the central portion of the mass by the external pressure, at some figure that would have no conceivable meaning for us in terms of tons per square inch; and in which also the temperature may be limited by the light pressure of the incandescent center repelling the in-pressing masses outlying so that the density and temperature of the total never reaches and never may reach the maximum it would otherwise attain. Light pressure is one of the smallest forces measurable, at present, in the laboratory; but, as it increases as the square of the temperature, it may prove yet to be one of the greatest forces in the huge uncompressed nebular masses of space, where the external temperature--as determined by spectroscopic readings--is probably between 20,000 and 30,000 degrees Centigrade. At any rate, this hypothesis of tremendous light pressure explains, as no other theory does, the fact that no masses in space, of more than a certain size, appear in a solid or compressed form, and the further fact that external temperatures above those mentioned have not been detected in any bodies so far studied. Internal temperatures are limited only by the room allowed for molecular vibration. In the line of physical research, though very highly advanced, Professor Einstein's Theory of Relativity, which seems, in some aspects at least, fairly well substantiated, hypothesizes an upper limit to space itself, that the extent of space is a tremendous but finite quantity. The

maximum velocity possible is also fixed, by the relativity theory, as the speed of light in a vacuum, 186,337 miles per second. Michaelson's latest value for the velocity of light is some 140 miles per second less than the older accepted figure.

Engineering Thermodynamics does not treat of exact physical limits, although it does consider that the heat form of energy is the form towards which all other forms are evolving, and that the temperature factor, or measure of available energy, is constantly decreasing in value, while the entropy factor, the measure of unavailable energy, is constantly increasing. In other words, engineering theory and practice at present holds that mechanical, chemical, electrical, and the other high-grade forms of energy, are being slowly transformed into the lower grade heat form, and that that heat form is becoming less and less available for doing work. This is the law of the Degradation of Energy, otherwise known as the Second Law of Thermodynamics--the First Law of Thermodynamics being a special case of the general Law of the Conservation of Energy. The First Law states that whenever work is transformed into heat, the heat produced is proportional to the work expended, or, when heat energy is made to do work, there is a constant ratio between the heat transformed and the work done. The Second Law states that heat can not pass from a colder to a warmer body without some compensating action taking place. It is impossible by means of a self-acting machine unaided by any external agency to convey heat from one body to another at higher temperature. No change in a system of

bodies that can take place of itself can increase the available energy of the system.

Further than these laws, the limits imposed by or upon Engineering or Mechanical Thermodynamics are those of mechanical practice and working ability, as, for instance, the maximum pressure under which a steam boiler will operate efficiently, or the maximum temperature that the blading of a gas turbine can stand.

In Thermo-chemistry a law (the First Law of Thermo-Chemistry) is met with which, like the First Law of Thermodynamics, is a special form of the Law of the Conservation of Energy. This thermo-chemical law states that the amount of heat required to decompose a chemical compound into its elements is equal to the heat evolved when the elements combine to form the compound.

But in Chemistry we meet with a number of limits of smallness, among which are the molecule--the smallest portion of a compound that can exist as that compound substance, and already mentioned in connection with Physics--, the ion--the smallest amount of a radical that has still the properties of that radical--, and the atom--the smallest amount of a chemical element having still the qualities of that element.

A feature of chemical compounds of interest from a thermo-chemical viewpoint is that endothermic compounds, or those in which heat is absorbed in the formation of the compound, are comparatively unstable and will readily decompose, sometimes violently; while exothermic compounds, or those which give off heat as the compound is formed and which include most compounds, are usually quite stable.

Physical Chemistry offers perhaps the most interesting and certainly some of the most involved ideas concerning limits and characteristics of the fundamental concepts. The Electron Theory begins where Chemistry leaves off and divides the atoms of all substances or elements into just two kinds of substance--protons, or minute indivisible bits of positive electricity; and electrons, the smallest and electrons, the smallest and indivisible quantities of negative electricity. The different elements are formed from these two basic substances by varying numbers and arrangements. The general arrangement is, however, the same in all elements; the center or nucleus of the atom is made up of one or more protons, while the electrons rotate at a very high velocity about this nucleus of protons as the planets do about the sun. Usually the numbers of protons and of electrons are equal, but it is possible for an electron to become detached from one atom and attached to another, leaving the first with an excess of negative electricity or a negative charge. This brings us down to the ultimate limit of divisibility of matter, and also leads us, by the aid of the relativity theory, to consider the transformation of one of these smallest possible particles of matter--the electrons--into pure energy radiating out, in the form of added turbulence in the surrounding atoms, from the electron thus transformed.

Professor Planck has then hypothesized a minimum amount or quantity of motion or energy, the quantum, which amounts to 6.55×10^{-27} ergs x seconds, developed thus:

Velocity equals Length x $time^{-1}$.

Energy " Mass x $velocity^2$

" Mass x $length^2$ x $time^{-2}$.

Quanta " Energy x time

" Mass x $length^2$ x $time^{-2}$ x time

" Mass x $length^2$ x $time^{-1}$.

Since the erg is the smallest unit of work or energy and the second the smallest general unit of time, the value of the quantum is given in terms of these two constants; or 1 quantum equals 6.55×10^{-27} erg seconds. The general rule for the use of quanta is that if a system vibrates with a certain frequency it can exchange energy with other systems only in amounts which are exact multiples of the product of this vibration rate multiplied by the value of one quantum, as given. Planck has modified this theory twice, first to say that energy could be emitted continuously by a system, but could be absorbed only in multiples of the product mentioned; and later to reverse this stand and maintain that emission occurred only when the energy to be emitted reached a value an exact multiple of the product spoken of, while absorption of energy could occur continuously. Either of these views explains quite satisfactorily many puzzling phenomena; while neither of them, by itself, accounts satisfactorily for some other phenomena observed by scientific investigators, and must be supplemented by other, and probably less well supported, hypotheses. Of course, to the layman, and even to the average professional man dealing as engineer or physicist with the different forms of energy, the quantum theory makes little

difference; but, when further developed, there is no telling what difference it may make.

Now we have seen that science has given us indivisible limits of mass and energy, and maximum limits of space and velocity, while the very recent researches of Professor Milliken seem to indicate another step taken towards the discovery of the least amount of movement in the amplitude of vibration of his recently discovered "penetrating rays" which have a higher frequency, as well as a much more penetrative effect--going through 6 to 17 feet of solid lead, to 1/2 inch for the "hardest" x-rays--than the ordinary x-rays, What all this seems to be leading to is that there is, similarly and necessarily, a minimum and indivisible unit of time, a period of least change of position of mass or of least change of form of energy, which would seem to be, before being mathematically worked out, a decimal multiple of 10^{-20} or even 10^{-30} seconds.

With this idea in mind, and also considering the present theory of the relativity of space and mass and energy, we can finally discuss all our fundamental, or what were yesterday called fundamental, concepts in terms of one basic concept, which, for lack of a better term, we shall herein refer to as "Inertia." This becomes evident in two forms or phases and in various and varying degrees of balance between, and forms of, these two phases, the static and the kinetic, from the minutest bit of matter and amount of energy to the vast reaches of interstellar space and the complicated processes of the human mind itself. If the basic concept is inertia, and

its basic phases are static and kinetic, then the two supposedly most fundamental concepts, mass and energy, that are considered in the relativity theory as related and interdependent, probably furnish the best and chiefest examples of the two phases; so mass may be considered as static inertia, and energy, pure energy, as kinetic inertia. Other fundamental concepts are definable likewise in terms of this basic concept. Space becomes the extension of inertia, and time the number of least changes in distribution, and balance between the phases of inertia, when time is measured by the minimum unit heretofore hypothesized.

A rather philosophical definition of space is "the range of experience." This, of course, is but the expression "the extension of inertia," brought down to ordinary experiences. Time has been defined as "the duration of experience," or the duration of being, measured by the process of happening," which means the same as "the measurement, numerically, of changes of inertia forms, phases, and distributions," or "the comparison of the continuity of one phase of inertia with the discontinuity of another phase," matching the definition of space as "the range or degree of extension of change of condition of inertia."

Considering time in terms of number of least changes and other physical concepts as varying in multiples of these least changes, it can be seen where mathematics becomes not only one of the most useful, as it is now, but also one of the most real and concrete, of the sciences, THE SCIENCE. As our limits, one by one, become fixed scientifically at the

lower end of the scale, the term "derivative" as used in Calculus takes on a more and more definite meaning and absolute value, depending, of course, on the variables and numbers considered. There appears, just now, to be no good reason for assuming that space is infinitely divisible; in fact, as before stated, recent researches tend to establish that indivisible unit of space corresponding to that reached in so many other physical concepts. It may even be possible that there is a least change of direction, although there seems to be no necessity as yet for such a hypothesis.

From these basic hypotheses, then, it should be possible to define all other physical terms as relationships of the static and kinetic manifestations of inertia with a numerical value of least changes in form, arrangement, and distribution of inertia. The only obstacle to a complete mathematical demonstration of these relationships is the lack of knowledge of the value of the basic unit of time. Attempts havê been made to derive this value mathematically by trying to find a common factor to the periods of infra-red and x-ray vibrations, but this method gave no factors that were common and irreducible. It may be hoped that, when complete data on Millikan's "penetrating" rays are available, that the vibration period of these rays will lead us a step nearer the ultimate division of time. Mathematical examinations of the penetrating effects of infra-red and waves of even higher frequency have thus far offered no sight of the more or less exact value of the elusive unit. Curves drawn on both rectangular and logarithmic graph paper showed very little direct correlation between frequency and penetration. In this connection, Dr. George K.

Burgess, Director of the Bureau of Standards, has the following to say:

1. "For long electromagnetic waves, including radio waves, electrical conductors such as metals absorb the waves, while insulators are in general transparent; though insulators differ in marked degree in their transmission for the higher frequencies.

2. As we approach frequencies of infra-red and visible light, no simple generality can be made except that metals are in general opaque. Gold, however, in the thinnest films transmits green light appreciably. In the near ultra-violet nearly all solids and liquids become opaque. Water is opaque for wavelengths less than 1800 AU (Angstrom unit equals 10^{-8} cm). From 1000 to 5 AU is a region where all materials are almost completely opaque. From 5 to .05 AU (the region of ordinary x-rays) all substances increase enormously in transparency, and roughly speaking the transmission depends only on the density of the substance.

3. An approximate rule applicable to all chemical elements at the shorter wavelengths is that the absorption is proportional to the number of atoms per unit volume times the fourth power of the atomic number times the cube of the wave length. Water will be relatively transparent, steel intermediate, and both lead and gold very opaque. In the 100 fold range of wavelength of x-rays, the absorption of any one substance will vary a million fold."

This approximate rule put in the shape of a formula may be expresses by A equals K $\frac{N}{V}$(mu)^4 (lamvda)^3, but its

extreme approximation makes it of little value for careful comparisons.

Another method that has been investigated is that of determining the velocity of impulse transmission in solids. From results of such determinations as applied to and derived from very small bodies, very small time intervals may be computed. Devices for testing out this speed of impulse transmission, by noting the time interval required for the far end of a rod to get in motion after the nearer end has been struck a sharp blow, have been designed; but have not as yet been constructed or tried out. One such device operates as follows:

A fairly long rod equipped at each end with a marking needle, pointer, or pencil, rests on guide rollers as nearly frictionless as possible. Rotatable discs are mounted on a shaft parallel to the bar, so that the pencils are each the same distance from the nearest disc as the other. The shaft carrying the discs has a slow translatory motion at right angles to its axis and in the plane of its axis and the bar, as well as a rapid rotatory motion. A gravity or spring actuated hammer strikes one end of the bar and sets it in motion longitudinally. The discs are rotated at high speed by a drive pulley midway between them. The pencils at either end of the forced bar record on the discs the exact time the particular end of the bar moves; the motion of the shaft with its bearings towards or away from the bar prevents the pencils from simply making circles in which the beginning is indistinguishable, but causes them to produce instead a spiral. Checking up to make sure that the discs zero all right at high speeds is done by another apparatus which causes two other

pencils to strike simultaneously one on each disc. The discs must be driven at constant speed; and friction must be eliminated as far as possible, while all connections are still made to allow a minimum of play. Different cross-sections, and cross-sectional areas should be used for bars of the same material, and different materials of identical mass, volume, or section should be tried out; while the apparatus should be used in at least the four cardinal directions of the compass and the four intermediate directions, to eliminate magnetic, electromagnetic and other effects that might have a bearing on the results obtained. Of course the length of the bar and the angular velocity of the discs are readily secured, and the development of the velocity with which the movement of the bar is transmitted is then a matter of comparatively simple arithmetic. However, mechanical difficulties make the operation of the apparatus less simple than the general principles here outlined would indicate, and a successful construction would result only from long, patient, and painstaking labor.

After abandoning the experimental method for the time being, recourse was had to pure theory by which a formula was developed for the time it should take for an impulse to travel the length of any certain bar. It is to be understood that the impulse is one of translatory motion and not of compressional vibration (sound) for which the theoretical formula is V equals the square root of e/d, which checks out most accurately in experimental work. (V equals velocity; e equals coefficient of elasticity; and d equals density in the sound velocity formula).

Several assumptions must necessarily be made in any

theoretical development; and we have no exception in this case. The problem may be stated: A rod lying horizontally on a frictionless table is struck on one end by a hammer moving axially with the rod. How long is it before the far end of the rod moves?

We assume first that the resultant final velocity of the rod compared to that of the striking hammer is governed strictly by the laws of elastic impact and conservation of momentum. Next we assume that the farther end of the rod remains fixed at first and that the rod is simply compressed by the force of the blow; the end struck remains fixed and far end of rod is moved by expansion of the rod. Also since force of rod in expanding equals force required to compress it, and mass moved in expansion equals mass moved in compression; therefore acceleration, space, velocity, and time of expansion equals same of compression.

Finally we assume that the kinetic energy disappearing in the collision is all used to produce compression in the rod.

These many postulates naturally make the formula entirely theoretical; but evidently they will hold increasingly well with smaller and smaller rods and consequent shortened time intervals, which are the cases in which we are most interested. In developing this formula, we will use symbols for physical characteristics as follows:

Rod	Symbolism	Hammer
L	Length	l
A	Cross-sectional area	a
E	Coefficient of elasticity	e
M	Mass	m

Rod	Symbolism	Hammer
C	Amount of Compression	c

v equals velocity of hammer before impact

V " " " " and rod after impact

mv " $(m \text{ plus } M)V$. V equals $\frac{mv}{m \text{ plus } M}$

Kinetic energy of hammer before impact equals $K\text{-}E_1$

$K\text{-}E_1$ equals $\frac{mv^2}{2g}$

Kinetic Energy of hammer after impact equals $K\text{-}E_2$.

$K\text{-}E_2$ equals $\frac{mV^2}{2g}$ equals $\frac{m\left(\frac{mV}{m \text{ plus } M}\right)^2}{2g}$ equals $\frac{m^3v^2}{2g\,(m \text{ plus } M)^2}$

Kinetic Energy of rod after impact equals $K\text{-}E_3$

$K\text{-}E_3$ equals $\frac{MV^2}{2g}$ equals $\frac{M\left(\frac{MV}{m \text{ plus } M}\right)^2}{2g}$ equals $\frac{Mm^2v^2}{2g\,(m \text{ plus } M)^2}$

$K\text{-}E_4$ equals $K\text{-}E_2$ plus $K\text{-}E_3$ equals $\frac{m \text{ plus } M}{2g}V^2$ equals $\frac{m \text{ plus } M}{2g}\left(\frac{mV}{m \text{ plus } M}\right)^2$

$K\text{-}E_4$ equals $\frac{m^2v^2}{2g(m \text{ plus } M)}$

Energy used up in producing compression equals

$K\text{-}E_1 - K\text{-}E_4$ equals $\frac{mV^2}{2g} - \frac{m^2V^2}{2g(m \text{ plus } M)}$ equals $\frac{mV^2}{2g}\left(1 - \frac{m}{M \text{ plus } M}\right)$ equals $\frac{mv^2}{2g}\left(1 - \frac{V}{v}\right)$.

Force required to produce compression C equals $\frac{C}{L} \cdot \frac{E}{A}$ equals $\frac{CE}{LA}$.

Average force during compression equals $1/2\ \frac{CE}{LA}$.

Work done in compression of rod equals $C \cdot \frac{1}{2}\frac{CE}{LA}$ equals $\frac{\frac{1}{2}C^2E}{LA}$ equals $K\text{-}E_1 - K\text{-}E_4$ equals $\frac{mv^2}{2g}\left(1 - \frac{V}{v}\right)$

Action and reaction being equal, compression in hammer will be equal but opposite to that in rod and may be neglected in considering effect on rod. (If hammer area or

elasticity is large compared to that of rod).

$$\frac{C^2E}{LA} \text{ equals } \frac{mV^2}{g}\left(1 - \frac{m}{M \text{ plus } m}\right) \text{ equals}$$

$$\frac{mv^2}{g}\left(\frac{M \text{ plus } m - m}{M \text{ plus } m}\right)$$

$$\frac{C^2E}{LA} \text{ equals } \frac{mV^2}{g}\left(\frac{M}{M \text{ plus } m}\right)$$

$$\frac{M \text{ plus } m}{M} \cdot \frac{g}{m} \cdot \frac{C^2E}{LA} \text{ equals } v^2$$

v^2 equals $2\alpha C$, α equals negative acceleration of hammer.

$$\alpha \text{ equals } \frac{V^2}{2C}$$

Time of acceleration equals t.

V equals α t. t equals $\frac{V}{\alpha}$ equals $\frac{2Cv}{V^2}$ equals $\frac{2C}{v}$

equals $\frac{2\cancel{C}}{\cancel{C}}$ times the square root of $\frac{LAMm}{(M \text{ plus } m)gE}$

t equals 2 times the square root of $\frac{LAMm}{(m \text{ plus } M)gE}$.

t equals time of compression equals time of expansion.

Time of transmission equals T equals 2t.

T equals 4 times the square root of $\frac{LAMm}{(m \text{ plus } M)gE}$

equals 4 times the square root of $\frac{LAMV}{gEv}$

This formula applied to bodies of atomic size should give very small time intervals. For instance, if an electron, the smallest possible hammer, travelling with any velocity, were to hit the outside (orbit of the electron in the atom) of a hydrogen atom, which is probably the smallest body having a (postulated) finite coefficient of elasticity, how long would it take the impulse to travel the radius of the hydrogen atom?

In the formula T equals 4 times the square root of $\frac{LAMm}{(m \text{ plus } M)gE}$, modern physical chemistry gives us the following values:

L equals radius of orbit of Hydrogen atom equals 5×10^{-9} cm.

A equals cross-sectional area of Hydrogen atom equals $(5 \times 10^{-9})^2$ pi cm^2.

M equals mass of Hydrogen atom equals $\frac{1}{6.06 \times 10^{23}}$ grams.

m equals mass of electron equals $\frac{M}{1847}$ equals 9×10^{-28} grams.

g equals acceleration due to gravity equals 980 cm per sec.^{2}.

It is thus seen that we have everything but E, the coefficient of elasticity of the atom, which has not been determined as yet. Born and others have computed the coefficient of elasticity as between atoms in molecules of various salts; but this case requires the interior coefficient of elasticity of the atom proper, rather than the measure of the elastic effect as between atoms or molecules of the element hydrogen.

By some means, however, this minimum time unit will be evaluated; and scientists will have another final division to work with, in considering energy transfers and transformations. The rather unfortunate thing about these energy transformations is that, while life and other conditions on the earth are not exactly dependent upon a certain quantity of other forms of energy--a wide variation in the amount of electrical, chemical, or mechanical energy existing in a given system being permissible, sometimes from practically zero to very large amounts--the demand of most organisms and systems for an amount of heat energy with a comparatively high intensity factor or temperature--compared to the absolute zero of temperature--makes it necessary to waste large amounts of heat energy, because of this high temperature below which the heat energy is unavailable. Also the other forms of energy seem to have a tendency to change to

this more wasteful heat form. Perhaps further research with these least units of matter, energy, and time will tell why.

Milliken believes the very high frequency rays he has found in existence are caused by the formation of atoms of the elements as we know them, from the basic protons and electrons somewhere out in space, some of this matter being changed to energy as manifested by the short wave-length electromagnetic vibrations. So the constant tendency noted in terrestrial practice for energy to become slower in its vibration rate and more and more unavailable may mean a return from the kinetic phase of inertia to the static phase, or, in other words, the retransformation of energy back into matter, taking place so gradually and steadily and over so large a portion of our range of experience that it has hardly been noticed as such. This completion of the cycle of changes of phases or manifestations of inertia is satisfying from a philosophical standpoint, anyway, even though we have not as yet sufficient scientific evidence to more than hint at its proof.

All forms of energy are finally considered as more or less mechanical; and thermodynamics treats of the relation between heat energy and mechanical energy; while it has generally been held that all other forms of energy tend to degenerate into heat energy and of the lowest grade in which the temperature, or measure of the kinetic molecular energy, tended towards a minimum, and the entropy, or measure of unavailable energy, tended towards a maximum. So we see, that, broadly speaking, thermodynamics covers practically the whole field of energy, and certainly every phase of the study of

BIBLIOGRAPHY

Books

A System of Physical Chemistry, Vol. III, Lewis.
An Advanced Course of Instruction in Chemical Principles, Noyes.
Applied X-Rays, Clark.
Audel's Gas Engine Manual
College Physics, Kimball
Dictionary of Applied Physics, Vols. I, III, IV, and V, Glazebrook.
Encyclopedia Brittanica, 11th Edition.
Elements of Physical Chemistry, Jones.
Experimental Engineering, Carpenter and Diederichs.
Elementary Physical Chemistry, Taylor.
Engineering Thermodynamics, Lucke.
Gas Turbines, Marks and Danilov.
General Physics, Ferry.
General Physics for Colleges, Webster, Farwell, and Drew.
Guldner's Internal Combustion Engines, Diederichs.
Handbook of Chemistry and Physics, Hodgman and Lange.
Hydraulics, Hughes and Safford.
Internal Combustion Engines, Carpenter and Diederichs.
Introduction to Contemporary Physics, Darrow.
Kinetic Theory of Gases, Loeb.
Mechanical Engineer's Handbook, Marks and Loewenstein.
Physics for Colleges, Sheldon, Kent, Paton, and Miller.
Physics for College Students, Knowlton.
Physical Chemistry, Ewell.
Physical Chemistry, Lincoln.
Physical Chemistry in the Service of the Sciences, van't Hoff and Smith.
Practical Thermodynamics, Cardullo.
Problems of Modern Physics, Lorentz.
Proceedings of the American Chemical Society for 1913, January, Lewis.
Reflections on the Motive Power of Heat, Carnot and Thurston.
Service Chemistry, Lewis.
Steam and Gas Turbines, Stodola and Loewenstein (also Dampf und Gas Turbinen, Stodola).
Steam Turbines, Moyer.
Technical Thermodynamics, Zeuner.
Text-Book of Modern Physics, Weld and Palmer.
Thermochemistry, Thomsen,
Thermodynamics, Emswiler.
Thermodynamics and the Free Energy of Chemical Substances, Lewis.
Thermodynamics and Chemistry, Duhem and Burgess.
Thermodynamics and Chemistry, Nernst.
Thermodynamics of Technical Gas-Reactions, Haber and Lamb.
The Scientific Papers of J. Willard Gibbs, Vol. I.
X-Rays and Electrons, Compton.

Magazines

Automotive Industries
Electrician
Engineer
Engineering
L'Illustration
Mechanical Engineering
Marine Engineering and Shipping Age
Power
Power Plant Engineering
Scientific American

ROOM USE ONLY

ROOM USE ONLY

MICHIGAN STATE UNIVERSITY LIBRARIES
3 1293 03056 1702