RATIONAL PSYCHROMETRIC FORMULAE
THEIR RELATION TO THE PROBLEMS OF METEOROLOGY AND OF AIR CONDITIONING

By Willis H. Carrier

ABSTRACT OF PAPER

In many industries such as the manufacture of textiles, food products, high explosives, photographic films, tobacco, etc., regulation of the humidity of the atmosphere is of great importance. This paper deals with the subject of the artificial regulation of atmospheric moisture, technically known as air conditioning. It gives a theoretical discussion of the subject in which formulae are developed for the solution of problems. These formulae are based upon the most recently determined data and in order to establish a logical basis for the presentation of these data and the derivation of the formulae, the principles governing atmospheric moisture are reviewed and the present methods of determining atmospheric humidity are discussed.
THE TEMPERATURES OF EVAPORATION OF WATER INTO AIR
AN EXPERIMENTAL DETERMINATION OF THE LAWS
GOVERNING THE DEVIATION OF THE ACTUAL
TEMPERATURE OF EVAPORATION FROM
THE THEORETICAL

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THE AMERICAN SOCIETY OF
MECHANICAL ENGINEERS
29 WEST THIRTY-NINTH STREET, NEW YORK

Presented at the Annual Meeting of the Society, New York,
December 1 to 4, 1924

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advanced in papers or discussions (E2, Part. 3)

Technical Paper 2: The Temperatures of Evaporation of Water into Air, 1924
[American Society of Mechanical Engineers]
Comparison of Thermodynamic Characteristics of Various Refrigerating Fluids
With Reference to Their Adaptability for Both Positive and Centrifugal Compression

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and
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Reprinted from the June, 1924, issue of Refrigerating Engineering, published by the American Society of Refrigerating Engineers, 55 Warren St., New York, N. Y. The Society is not responsible for opinions advanced in papers or discussions.
Centrifugal Compression as Applied to Refrigeration

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Reprinted from February, 1926, number of Refrigerating Engineering, published by The American Society of Refrigerating Engineers, 35 Warren Street, New York, N. Y.
The Society is not responsible for statements or opinions advanced in papers or discussions

Technical Paper 4: Centrifugal Compression as Applied to Refrigeration, 1926
[American Society of Refrigerating Engineers]
Air Conditioning in the Printing and Lithographing Industry

To prevent any moisture, which is in the air, condensing on the paper and causing damage, the air must be kept at a constant relative humidity. This can be achieved by using a humidifier or a constant temperature in the printing area. The ideal temperature for most printing operations is between 65° and 70° F (18° and 21° C), and the relative humidity should be maintained at 45% to 55%. This ensures that the paper is neither too dry nor too wet, which can affect the printing process.

The paper should also be allowed to adjust to the room temperature before it is printed. This allows the paper to absorb or lose moisture to reach the desired humidity level. Once the paper is at the correct humidity, it can be printed without any issues.

In conclusion, air conditioning and proper humidity control are crucial for a successful printing process. By maintaining the correct temperature and humidity, the paper will dry properly, and the prints will come out clear and crisp.

Technical Paper 5: Air Conditioning in the Printing and Lithographing Industry, 1929 [The American Society of Mechanical Engineers]
The Control of Humidity and Temperature as Applied to Manufacturing Processes and Human Comfort.
(Paper No. 391)
By Willis H. Carrier 1)

The control of atmospheric conditions within an enclosure with reference to temperature, humidity, and cleanliness is termed "Air Conditioning." The importance of this field of engineering has of late years become widely recognized, not only in engineering circles, but by the public at large. Perhaps this is best evidenced by the fact that the forthcoming edition of the Encyclopedia Britannica will contain a chapter devoted exclusively to air conditioning. Such chapters are already found in some of the leading engineering hand-books.

It has long been recognized that relative humidity is an important factor in the manufacture and processing of certain hygroscopic materials such as textiles. Since the normal relative humidity in textile factories is nearly always lower than that desired, various means have for many years been provided to increase the humidity by artificial means.

On the other hand, there are industries which require a definite and unvaried humidity so that at some periods the normal quantity of moisture in the air must be increased, and at other times lowered. Among such industries may be mentioned the manufacture of confectionery, the processing and weaving of artificial silk, and the printing and lithographing industry.

Other industries require not only a constant relative humidity, but also a fairly uniform temperature. An example of this is seen in the modern automatic wrapping machines used for wrapping chewing gum, food products, confectionery, and machine made cigarettes, which require exact conditions of heat and moisture in order to function satisfactorily without frequent adjustments.

In the manufacture and processing of most hygroscopic materials there is usually one or more stages in the process in which moisture has to be removed from the material. In all such products which are not in themselves soluble in water, this is usually accomplished by air drying.

In a very large portion of them, in order to avoid injury to the products which require temperature and humidity control, the rate of moisture removal must be controlled with accuracy in certain stages of the process, while at the end of the process of drying it may be extremely important to control with

1) Assisted by an Advisory Committee appointed by the American Society of Heating and Ventilating Engineers as follows:
Prof. A. G. Wilard. O. W. Armspach. H. W. Ellis
R. E. Sull.
A Review of Existing Psychrometric Data in Relation to Practical Engineering Problems

BY W. R. CARPENTER, Newark, N. J., and C. O. MACKAY, Ithaca, N. Y.

The authors review and correlate available psychrometric data, and discuss the application of these data to engineering problems. They analyze and correlate existing data with reference to deviations of observed wet-bulb temperatures from those of true adiabatic saturation. The paper also includes a tabulation of refted psychrometric values in accordance with the latest physical data with correction factors for all normal variations of atmospheric pressure. The purpose of this is to permit the ready use of such psychrometric data for any other engineering problem not involving evaporative processes. The latter is a device that has long been needed and is of particular value in computer calculations of data.

Objectives. An analysis and a summary of the proper method of employing the important and useful psychrometric heat function, previously defined by Carrier in 1851, is presented in this paper. This function will also be termed the "psychrometric chart." It is given by the heat of saturation, which includes the heat of the liquid.

In view of the present wide employment of psychrometric data in various fields, and particularly in the field of air conditioning, and also in view of the fact that there have been numerous questions raised as to the limits of accuracy of existing data, it seems appropriate to review and correlate, as far as possible, the past research in this field to sharpen the application of these data to engineering problems.

In summary, the analysis and correlation of existing data, which includes the following:

1. The analysis and correlation of existing data, as presented by the authors, is of particular value in computer calculations of data.

2. The authors' objectives are to provide a basis for the proper method of employing the psychrometric heat function, previously defined by Carrier in 1851, and to present this function in a form that is easy to use.

3. The psychrometric chart is given by the heat of saturation, which includes the heat of the liquid.

4. The past research in this field is reviewed to sharpen the application of these data to engineering problems.

5. The authors emphasize the importance of accurate data and the need for a more systematic approach in the future.

6. The psychrometric chart is presented in a form that is easy to use, and it is given by the heat of saturation, which includes the heat of the liquid.

Technical Paper 7: A Review of Existing Psychrometric Data, 1936
[The American Society of Mechanical Engineers]
The Contact-Mixture Analogy Applied to Heat Transfer With Mixtures of Air and Water Vapor

By W. J. Carrier, Newark, N. J.

The author derives and discusses the general contact-mixture formula for representing physical processes of heat transmission and fluid friction, and points out that the contact-mixture analogy serves directly and logically to correlate heat transfer with fluid friction. He compares the analogy with the conduction-diffusion theory and relates why the contact-mixture analogy exists all the phenomena connected with gas flow and heat transmission.

HERETOFORE in literature, it has been customary from the time of Reynolds to analyze heat transfer and conduction to flow of gases by using an analogy to the flow of viscous fluids. While this method can be made to give a fairly good correlation of the phenomena of heating and frictional resistance of gases it is not representative of the actual physical process, and it is not really applicable, for example, to compressing and evaporating of water vapor into air except by the application of another analogy. The author believes it to be quite in line with modern physical thought to state that there can be no such thing as shear in a gas and therefore there can be no true viscosity. Also, probably, there is no true conduction in a gas as in liquids but only diffusion of molecules continuously in motion. Any gas is made up of molecules having different velocities, i.e. different temperatures. The energy of the molecule (i.e., the absolute temperature) varies directly as the square root of its molecular velocity. Therefore, the average temperature of a gas composed of molecules having different molecular velocities is the average of the square root of their respective velocities. Wedley, at least, does not always occur when a gas contacts a surface at a different temperature. We know, however, that molecules in contact with a hotter surface are heated, i.e., their molecular velocities increased and those high-velocity molecules are diffused and are mixed with other molecules of the gas which have not been so heated. Whether they retain their identity or high-velocity molecules (which is to be doubted) or whether they impart a portion of their kinetic energy to the adjoining molecules, which do not contact the surface, is immaterial so far as any study of heat transmission is concerned. The average of the square roots of the velocities, i.e., the total energy is the same whether they retain their energy or whether they impart part of their thermal energy to other molecules.

In the process of pure heat conduction to gases, there is no mechanical mixture or disturbance due to gravitational effect (convection) but only intermolecular diffusion, which depends upon the varying permanent properties of the gas and its transient condition. The rate of heat diffusion, however, is found approximately, to obey exactly the analogous laws of heat conduction, that is, it is directly proportional to the distance and to the temperature difference between two boundaries. In a steady state of heat flow, there is a temperature gradient in a solid, although in the first case, the temperature gradient is due solely to material transport, while in the second case, it is due to the passage of heat from one molecule to another.

These rather obvious and elementary statements are made in the present in order that there may be no misunderstanding of the basis upon which the problem is approached.

When a gas is forced to pass over a surface at a relatively high velocity, as for example, between plates or through a pipe, the mainstream of air is turbulent above certain critical velocities. However, at all velocities there are two nonturbulent films. The first, which is probably a laminar or molecular in thickness, is necessarily a dense film of unmixed gas in which approximately the density of liquid or, in some conditions, greater than that of the liquid. This would appear to be a polar layer. The second, a film or zone in which there is a laminar flow. The film is distinguished from a turbulent flow, i.e., all the particles are moving in parallel lines. There is no molecular mixture within this film. Particles pass from the surface film through the laminar film only by diffusion and heat is conducted only by the process of diffusion, just as though there were no motion whatever within the film since the actual motion is at right angles to the effective path of molecular diffusion. In this film, warm (contacted) particles pass outward by diffusion white cold (uncontacted) particles, and also previously contacted particles, diffuse inward from the outer surface of the laminar film to the external film. In this process, there is no sharp boundary between the laminar and the external boundary of air, but a gradual increase of turbulence. However, from the standpoint of analysis of the current flow, the laminar film is a convenient boundary for a line of sharp demarcation. The thickness of the so-called laminar film does not change with the velocity. The thickness of the laminar film, however, varies directly with the velocity and at a somewhat lower rate, i.e., at a fractional power of the velocity.

There is a definite temperature gradient in the laminar film...
A Review of Existing Psychrometric Data in Relation to Practical Engineering Problems

BY W. H. CARRELL, NEWARK, N. J.; C. G. O. MACKEY, ITHACA, N. Y.

The authors review and correlate available psychrometric data in order to solve problems of the type described in the title. They analyze and correlate existing data with reference to deviations of observed wet-bulb temperatures from those of true adiabatic saturation. The paper also includes a discussion of revised psychrometric values in accordance with the latest physical data with correction factors for all normal variations of humidity. The author makes an analysis of the proper method of employing the psychrometric heat function previously defined as the "total heat less the heat of the liquid," and afterward referred to as psychometry as "total heat." For this function, the author offers the term "delta function," indicating it as the adiabatic or true total heat which includes the heat of the liquid.

In view of the present widespread employment of psychrometric data in various fields, and particularly in the field of air conditioning, and also in view of the fact that there have been numerous questions raised as to the limits of accuracy of existing data, it seems apparent to review and correlate, as far as possible, the past research in this field and to discuss the application of these data to engineering problems.

Introduction of Paper

Introduction of Paper

The analysis and correlation of existing data with reference to deviations of observed wet-bulb temperatures from those of true adiabatic saturation.

Objective of Paper

Objective of Paper

The analysis and correlation of existing data with reference to deviations of observed wet-bulb temperatures from those of true adiabatic saturation.

Second Objective: Presentation of revised psychrometric values in accordance with the latest physical data and correction factors for all normal variations of humidity. The purpose of this is to provide the ready use of standard psychrometric data charts for any other psychometric process without involved calculations. The latter is a device that has long been needed and in particular value in accurate determination of test data.

Third Objective: Analysis and demonstration of the proper method of employing the psychrometric heat function previously defined as the "total heat less the heat of the liquid," and afterward referred to as psychometry as "total heat." For this function, the author offers the term "delta function," indicating it as the adiabatic or true total heat which includes the heat of the liquid.

Conclusion of Paper

Conclusion of Paper

In the past 20 years, the majority of the engineering calculations involving humidity in air have been based on the psychrometric charts presented in 1911 by Carrier (1). The values given were based on several assumptions concerning data temperatures with existing psychrometer, and the calculated values of humidity saturation. The paper (1) showed that experimentally the two values were in close agreement. However, test data presented in the original paper (1) in 1911 indicated two sources of deviation of the wet-bulb temperature from the temperature of adiabatic saturation. The first was the humidity factor which was indicated by the difference between an unshaded wet bulb and a wet bulb completely shielded from radiation, and the second was the difference between the readings of a multi-shielded wet bulb and the observed temperature of adiabatic saturation, where the radiated wet bulb appeared to have lost more than one-tenth of the measurement. In view of this theory advance, the paper was written, however, that at the time it was done to remove the apparent error.

Later observations conducted by Arnold (2) and by Ubeppi (3) have shown the latter assumption to be incorrect and that it is not only valid, but in accordance with physical laws that the latter variation should exist. However, this two sources of deviation are in opposite directions tending to neutralize each other, and it has been proved that there is a definite air velocity when the wet-bulb temperature between the wet bulb (not shaded from radiation) and the adiabatic saturation of adiabatic saturation. Carrier's 1911 experiments (7) indicated this velocity fine line of approximately 2000 feet. Ubeppi's tests (3) would indicate it to be slightly over 2000 feet. Arnold (2) would be by air velocity of about 300 feet. Computations from his theory give a still slower value as shown in Appendix I. The authors' present correlation would indicate it to lie at an intermediate velocity

Technical Paper 9: A Review of Existing Psychrometric Data, 1936
[The American Society of Mechanical Engineers]
THE INVENTION OF
THE CENTRIFUGAL REFRIGERATING MACHINE
"PROPOSED" SCRIPT FOR A TAPE RECORDING
FOR THE SMITHSONIAN INSTITUTION
PLUS A COMPLETE HISTORICAL SKETCH

When the Smithsonian decided to display the compressor of the Original Centrifugal Machine, it requested a tape recording for the Archives. This type of description would institute a new practice, and consequently, there were no definite ideas about what it should be. To write the script was the original objective—but, as the story was developed by research and thought, it became increasingly evident that a complete coverage would be too long for an oral presentation.

There was entirely too much substance to the story for it to be left half told. The invention had projected a revolutionary development into the art of refrigeration; it had given a tremendous impetus to the development of air conditioning. The story had to depend too much upon the memories that were fading rapidly with age; and it had to draw a clear distinction between the Centrifugal Compressor that would constitute the sole exhibit and an entirely new method of refrigeration in which the compressor was only one of numerous functional elements.

This led to a plan by which one document could be made to serve two purposes: One was to provide an abridged version for the oral presentation, and the other was to provide a complete and well-rounded Historical Sketch for the studious reader and the Archives.

The division between short and long could be shown by the style of typing. The short would be double-spaced in full-length lines; and the long would consist of the short plus all that was single-spaced and indented. With a little extra effort, good continuity could be maintained and the reader could be given a free choice according to time and interest.

The idea may have had some merit; but as research brought more and more facts to light, length got more and more out of hand. The upshot was a complete change of plan. An appropriate history would be written in the original short-long style, divided into chapters, and reinforced with some last-minute illustrations—and the script for the tape could come later.

The author is not too happy about the length of the current edition (about 7500 words for the short, and 10,000 for the long); but he does feel that justice to the story has been reasonably well done.

Logan Lewis
March 1, 1962