# Willis H Carrier

## Father of Air Conditioning

*R V Simha*

**Willis H Carrier, the Father of Air Conditioning, placed the science of air conditioning on a firm scientific basis in the year 1911, in his paper 'Rational Psychrometric Formulae' – widely known also as the 'Magna Carta of Psychrometrics'. This paper was presented at the annual meeting of American Society of Mechanical Engineers (ASME). The centenary of this historic event happens to be the past year 2011. Amongst his many achievements are his contributions to development of the Psychrometric Chart (which remains essentially the same as the chart presented more than a century ago), the Law of Constant Dew-Point Depression, Dew-Point Control and the invention of the Centrifugal Refrigeration Machine.**

**His contributions to the industry, the way he tackled the technical and engineering aspects of his work, his business acumen and his leadership qualities are fairly well known. Also, recalled here are several episodes and anecdotes of his career and life, which present the pictures of 'Carrier, the Man', 'the Genius', 'the Leader' and other facets of his rich personality.**

**R V Simha is an air conditioning consultant and Director of Airtron Consulting Engineers Pvt. Ltd. based at Bangalore. His interests are mainly in the fields of comfort, climate and weather, psychrometry, energy aspects of air conditioning, sustainability and green buildings and natural/ passive cooling systems.**

### Carrier's Early Life

Willis Carrier was born in 1876 in a farm in the western parts of New York State. His father was Duane Carrier who settled down to farming after trying his hand at various other occupations. His mother was Elizabeth Haviland, whose forebears had settled in New England in the 17th century. She was a Birthright Quaker, the first in her family to marry outside her faith.

Carrier has often been compared to celebrities as Edison, Ford, and Bell and Wright Brothers.

**Keywords**
W H Carrier, rational psychrometric formulae, psychrometric chart, invention of centrifugal machine, law of dew-point depression.

Carrier was the only child to his parents. He played mechanics-oriented games, planned putting machines in such games so they would work. Before he was 9, Carrier was tackling the problem of a perpetual motion machine. He could not grasp the meaning of fractions; his mother explained it to him and it was only then that it took shape in his mind. Referring to this memorable episode, Carrier once said, "She opened up a new world to me and gave me a pattern for solving problems that I have followed ever since." "In one-half-hour", he said, "she educated me". His mother died when he was only 11 years old.

Carrier's attitude is unsurprising considering the backdrop of his forebears from Thomas Carrier and Martha Allen in the late 1600s down to his parents. Carrier described his forebears as "a rugged and adventurous people, with courage to try unknown" – qualities he himself possessed in no small measure.

### Carrier Works His Way Through College

Carrier was over 6 feet 6 inches tall, robust and athletic. He worked through his school (Angola High School) and proceeded to enter Cornell University from there. He was actively involved in several sports – basketball, skating, swimming and boxing. He worked hard and earned his way through college via scholarships and teaching, complemented by making money on odd jobs – mowing lawns, tending furnaces, distributing milk, waiting on tables and working as an agent for a boarding house. In the process, he set up a co-operative laundry agency (with another student friend), which became the first of many such student's co-ops in the United States. Carrier received a degree in mechanical engineering from Cornell University in 1901.

Carrier was not a conformist even in his school and college days. He was an independent thinker. He recalled his mother's advice – "Figure out things for yourself".

Carrier attributed his talents in mechanics and mathematics to inheritance from his mother.

### Young Carrier Looks at Air Conditioning from Scratch

Carrier did not invent air conditioning nor did he coin the term '*Air Conditioning*' nor install the first air-conditioning plant. Heating, humidifying, cooling and ventilation were all being done – even though not designed on any scientific and

**Box 1.**

**Temperature** is the measure of the intensity or level of heat.

**Dry Bulb Temperature (DB, db, DBT, dbt)** is the temperature registered by an ordinary thermometer. db represents the measure of sensible heat, or the intensity of heat.

**Wet Bulb Temperature (WB, wb, WBT, wbt**) is the temperature registered by a thermometer whose bulb is covered by a wetted wick and exposed to a current of a rapidly moving air having a velocity of around 5 m/s. WB is measured by a sling psychrometer which has a set of dry and wet bulb thermometers. The psychrometer is whirled at such revolutions per second that the velocity of the bulb will be 5 m/s approx (in still air).

**Relative Humidity (RH, rh);** (expressed in percentage) is the ratio of actual partial pressure of water vapour to its saturation pressure corresponding to the same db. Alternate definitions are – ratio of amount of moisture present in the air to the amount the same air holds at saturation at the same temperature, It indicates the ability of air to absorb additional moisture.

**Dew Point (DP, DPT) is t**he temperature at which water vapour in moist air starts condensing when it is cooled.

**Effective Room Sensible Heat (ERSH)** is the sum of all sensible heat gain that occurs in the room including the gain due to the portion of the ventilation air which is bypassed.

**Effective Room Latent Heat (ERLH)** is the sum of all latent heat gain that occurs in the room including the gain due to the portion of the ventilation air which is bypassed.

**Effective Room Total Heat (ERTH)** is ERSH + ERLH

**Effective Sensible Heat Factor (ESHF)** is the ratio ERSH/(ERSH + ERLH)

**Cooling Coil** – In an air conditioning system, air gets cooled when it passes through the cooling coil. Air is also dehumidified, in case, its dew point is higher than the cooling coil temperature.

**Contact Factor** is the part of the total air through the coil which comes in to 'contact' with the surface of the cooling coil.

**Bypass Factor** is part of the total air through the coil which fails to come into contact with the surface of the cooling coil.

**Apparatus Dew Point (ADP)** is the effective surface temperature of the cooling coil. It is also the temperature at a fixed flow rate at which both sensible and latent heat gains are removed (from the conditioned space) at the required rates. It is also often called as the 'Coil Temperature'.

**Humidity Ratio** is the weight of water contained in the air per unit of dry air. This is often expressed as kgs of moisture per kg of dry air or grams of moisture per kg of dry air (g/kg).

**Specific Volume** is the cubic meter of moist air per kg of dry air represented as $m^3$/kg.

*Box 1. continued...*

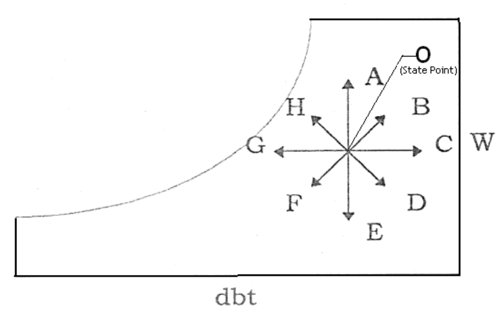
*Box 1. continued...*

**Enthalpy** is the heat energy content of moist air. It is expressed in kJ/kg and represents the heat energy due to temperature and moisture in the air. Lines of constant enthalpy (OH in *Figure* A) run diagonally downward from left to right across the chart. Lines of constant enthalpy and constant wet-bulb temperature lie close to each other. Accordingly, they coincide in many elementary charts, but with both values being indicated on the common line.

**TR** is cooling capacity in Tons Refrigeration (1 TR = 12,000 Btu/h).

**DX** (Direct expansion): In a DX plant the refrigerant directly expands into the cooling coils, evaporates therein and cools the air passing over the tubes and between the fins. It (the DX plant) may be compared with the chilled water plant in which the refrigerant cools water in the evaporator first and it is the water in turn, that cools the air thereafter.

**Brines** are liquids which are cooled by a refrigerant and used to transfer heat without change of state (unlike refrigerants which evaporate or condense to transfer heat). Water and solutions of salts like sodium chloride, calcium chloride and solutions of ethylene glycol and propylene glycol are examples of brines commonly used.




| | |
|---|---|
| dbt : | Dry Bulb Temperature |
| W : | Humidity Ratio |
| OA : | Humidification |
| OB : | Heating and Humidification: Stream Humidification |
| OC : | Sensible Heating |
| OD : | Chemical Dehumidification |
| OE : | Dehumidification |
| OF : | Cooling and Dehumidification |
| OG : | Sensible Cooling |
| OH : | Adiabatic Saturation |

**Figure A .** Different air-conditioning processes in psychrometric chart. A process starts from state point O. For example, OC represents sensible heating, increase in dry bulb temperature without change in moisture content. OA represents increasing moisture content without changing moisture content.

engineering basis but by experience, judgment and thumb rules. There were applications which called for cooling and dehumidifying. Cooling? – yes; but dehumidification – no, they had no clue. That was the situation at that time. As for coining its name, the credit belongs to, Stuart W Cramer, a leading textile engineer of the time, but it included only "humidifying and air cleaning and heating and ventilation".

Because of the rule of thumb techniques which were common practice at that time, Carrier believed that engineers were allowing excessively large "factors of safety" in designing and installing equipment and considered that these were really "factors of ignorance".

No one suggested that Carrier obtain more data and, in fact, few engineers recognized the need. But he posed the problem to himself and set about to find the answer. He did the necessary research – but confined it to only after working hours. His first study involved the reading of much published material on mechanical draft. The result was a formula for selecting draft fans for maximum boiler efficiency with minimum fan horsepower.

**Carrier Presents the Paper, 'Mechanical Draft'**

Carrier started his career at Buffalo Forge Company early in 1901. The company was involved in heating, drying and forced draft system[1]. At the end of just 6 months Carrier presented at the company's annual meeting a paper titled 'Mechanical Draft'. His paper was highly theoretical but on a very practical subject and, although it was delivered by a young engineer who had been with the company less than six months, it impressed everybody in the company. As a result, the company decided that Carrier should continue his research, not just after normal working hours but also during the regular working day itself. The lab that he founded later became an industrial laboratory – the first R&D Lab in the HVAC (Heating, Ventilation, Air Conditioning) industry. Carrier was just 25.

[1] A force draft system comprises intake openings, fans, ducting or other air conveying arrangements and exhaust openings, along with heaters and filters to ventilate and cool or heat an enclosure – usually, to maintain positive pressure.

Carrier had realised that except for physical and thermal properties of steam and air, there was no other data available. He carried out tests and obtained the data from which he derived equations and completed calculations.

**World's First Scientific Air-Conditioning System: 1906**

The problem which confronted Carrier was related to control of humidity "in the plant of Sackett–Wilhelms Lithography and Publishing Company of Brooklyn, New York". Printing was hampered by varying ambient conditions which caused paper to expand and contract. It was one size on a hot humid day and another on a hot dry day. When printing in color, similar distressing changes often occurred between runs – colors overlapped or failed to match those printed on another day. The flow of ink and its rate of drying were affected. The result was that the printers often had to reprint jobs or drastically reduce the speed of their presses in order to maintain quality. It didn't occur to him that here was a problem that could challenge his ingenuity or that finding a solution would be beyond his capabilities. How did Carrier solve this problem? The solution to this problem was the beginning of scientifically designed air-conditioned systems.

The basics of how air conditioning works are given in Appendix 1, and Appendix 2 takes a closer look at the psychrometric aspects of the Sackett–Wilhelms project.

**Air Conditioning Defined**

From this hard-earned knowledge and experience, came Carrier's classic definition:

*Air conditioning is the control of the humidity of air by either increasing or decreasing its moisture content. Added to the control of humidity are the control of temperature by either heating or cooling the air, the purification of the air by washing or filtering the air, and the control of air motion and ventilation*.

Carrier converted data obtained from his tests into equations, tables and graphs from which today's air-conditioning engineer calculates and makes equipment selections – (often by software) – the flow rate and temperature of chilled water and the flow rate through the coil required to cool and dehumidify each cubic foot of air to a specified temperature and relative humidity.

The Sackett–Wilhelms plant stipulated 70°F (21°C) in winter and 80°F (27°C) in summer, and a relative humidity of 55 % the year around. The plant consisted of heating coils and humidifiers (for winter). Cooling and dehumidification were accomplished by two sections of cooling coil – the first used well water and the second was connected to a refrigeration machine. The total installed capacity could have been around 55 TR (195 kW).

**Spray Water Température vis-à-vis Dew Point**

Successful as the plant was, Carrier was not happy; instead, he saw immediately that many improvements could be made. He found the solution to the problem of dehumidifying to exact chosen value of moisture content (of the cooled air). In his own words:

*Now, if I can saturate air and control its temperature at saturation, I can get air with any amount of moisture I want in it. I can do it, too, by drawing the air through a fine spray of water to create actual fog. By controlling the water temperature I can control the temperature at saturation. When very moist air is desired, I'll heat the water. When very dry air is desired, that is, air with a small amount of moisture, I'll use cold water to get low temperature saturation. The cold spray water will actually be the condensing surface.*

Being engaged in myriad activities, it took Carrier sometime to translate this concept of passing air through a spray of water to control dew-point temperature. It was only in 1904 that it was executed (in a spray washer) to his satisfaction. He applied for a patent and got it in early January 1906. He called his invention "An Apparatus for Treating Air". Around this time (1908), Carrier and his colleagues had quit Buffalo Forge Co. and formed a separate company – Carrier Air Conditioning Company of America.

**The First Spray-Type Air Conditioning Equipment**

The 'Apparatus for Treating Air' was the first spray-type air conditioning equipment. Using sprays of water for humidification was not a new concept but, ideas of removing water by using water itself was. This was so revolutionary that it was treated with incredulity and in some cases even with ridicule. Carrier's response was to publish the *Buffalo Air Washer and Humidifier Catalogue*. This was to inform and educate the market. The sale of the equipment began soaring thereafter.

**Law of Constant Dew-Point Depression**

Carrier landed on another priceless discovery at the same time – the Law of Constant Dew-Point Depression. This law says that within a wide limit the relative humidity of air remains constant as long as the difference between the dry-bulb temperature and the dew-point temperature is constant. (See *Box* 2.) Carrier based the design of an automatic control system on this discovery for which he filed a patent claim in 1907. He was thereby recognized as the inventor of 'Dew-Point Control'.

**The 'Magna Carta of Psychrometrics'**

Around this period, Carrier thoroughly investigated various aspects of the psychrometrics of evaporative cooling and indeed, of entire air conditioning itself. This led to the birth of the most significant and epochal document ever prepared on air conditioning – 'Rational Psychrometric Formulae'. His paper was presented on December 3rd 1911 at the annual meeting of the American Society of Mechanical Engineers. The era of dependence on empirical formulae deduced merely from simultaneous readings of dry bulb, wet bulb and dew-point temperature was over.

The following principles from Carrier's historic paper underline the entire theory of evaporative method of moisture determination as well as air conditioning.

i. When dry air is saturated adiabatically the temperature is reduced as the absolute humidity is increased, and the decrease of sensible heat is exactly equal to the simultaneous increase in latent heat due to evaporation.

ii. As the moisture content of air is increased adiabatically the temperature is reduced simultaneously until the vapor pressure corresponds to the temperature, when no further heat metamorphosis is possible. This ultimate temperature may be termed the temperature of adiabatic saturation.

**Box 2. Comments on Application of Law of Constant Dew-Point Depression (DPD)**

*Table* A and *Figure* A show the deviation of RH from the line of constant DPD for 3 cases: DB = 24°C, RH = 53.55%; DB = 24°C, RH = 50%; DB = 24°C, RH = 46.9% corresponding to 3 values of DPD (=10,11,12), where DPD = DB – DP. It will be seen that at any given constant DPD, the deviation is under 5% over a DBT variation of 16°C from 20°C to 36°C (note also that the error increases with DBT as well as DPD). For most engineering purposes, this error is negligible and therefore, a DPD line can denote the corresponding RH value. In most air conditioning apparatus the temperature of air leaving the apparatus will be close to the DP. This is especially so in the case of spray equipment (air washers). Accordingly, the difference between the room DBT and the supply air temperature (SAT) can be regarded as identical to the DPT. This way RH can be measured by sensing two temperatures only; no humidity measurement is involved. On rising room RH, the requirement is that the DPT should be increased. This can only be done either by raising the room DBT or by lowering the leaving air temperature (DPT or SAT).

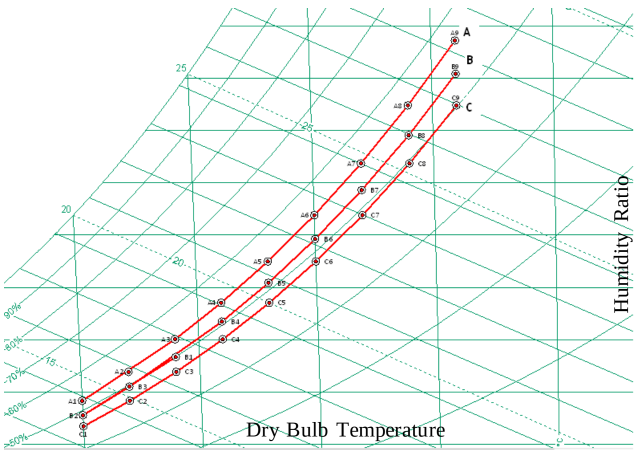



**Figure A.** Constant DPD lines (in red) are very close to constant RH lines (in green).

In practice, the DPT is kept constant and as the room DBT falls (during part load or rainy weather conditions), the supply air is heated (commonly called 'reheat') to restore the RH and thus maintain the DPD. This is what is known as 'Dew Point Control'. This simple scheme takes care of most comfort cooling applications.

| Description | A | | | | B | | | | C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DB °C | DP °C | RH % | DPD | DB °C | DP °C | RH % | DPD | DB °C | DP °C | RH % | DPD |
| Ref Pt | 24 | 14 | 53.55 | 10 | 24 | 13 | 50.00 | 11 | 24 | 12 | 46.99 | 12 |
| Max. | 36 | 26 | 56.56 | 10 | 36 | 25 | 53.11 | 11 | 36 | 24 | 50.20 | 12 |
| Min. | 20 | 10 | 52.50 | 10 | 20 | 9 | 48.89 | 11 | 20 | 8 | 45.58 | 12 |
| Max – Ref | | | 3.01 | | | | 3.11 | | | | 3.21 | |
| Min – Ref | | | –1.05 | | | | –1.11 | | | | –1.41 | |
| Average | | | 52.50 | | | | 48.89 | | | | 45.58 | |
| Range of RH Deviation | | | 4.06 | | | | 4.22 | | | | 4.62 | |

**Table A.** Calculations for cases A,B,C; these show that variation in RH is negligible for a constant DPD.

iii. When an insulated body of water is permitted to evaporate freely in the air, it assumes the temperature of adiabatic saturation of the air and is unaffected by convection; ie. the true wet-bulb temperature of air is identical with is temperature of adiabatic saturation.

From these three fundamental principles, a fourth was deduced:

iv. The true wet-bulb temperature of the air depends entirely on the total of the sensible and the latent heat in the air, and is independent of their relative proportions. In other words, the wet-bulb temperature of the air is constant, provided the total heat of the air is constant.

## The Impact of the 'Rational Psychrometric Formulae'

Carrier's paper was the all-important milestone in air conditioning. After its publication, engineers accepted the 'control of air' as a branch of their profession. Carrier's psychrometric chart was reproduced in engineering college and school textbooks since air conditioning as a subject began to be included in the curriculum. His 'Formulae' was translated into many foreign languages and became the authoritative basis for all fundamental calculations in the industry. It not only brought scientific recognition to Carrier, then only 35, but it can also be truly said that the industry which he and his colleagues had founded just a few years earlier (1906) had now come of age.

It is interesting to note in passing that the year 2011 marked the centenary of 'The Magna Carta'. *Figures* 1 and 2 serve to show how little today's psychrometric charts differ from those in the early years of the 20th century. Some common air conditioning processes are shown in *Figure* A in *Box* 1.

## The Invention of the Centrifugal Machine

Soon, Carrier was convinced of the inadequacy of the refrigeration machinery then in use. Eventually, he came out with a memorandum to his company titled 'Development Possibilities

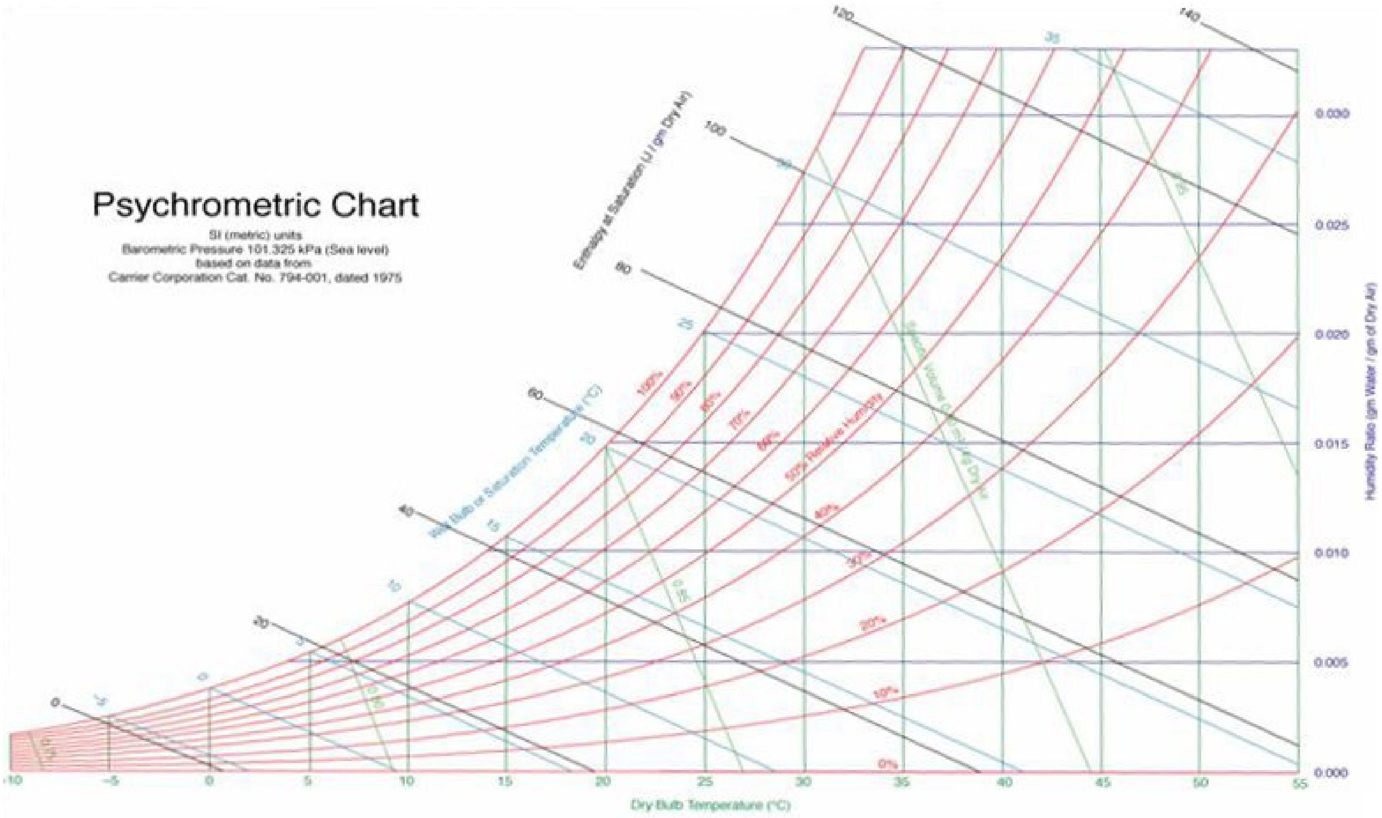



**Figure 1.** A typical psychrometric chart currently in use. This chart covers temperature range of –10 to 55° C and humidity ratio from 0 to 0.03g/g (=30g/kg). The different sets of lines correspond to constant values of various properties: dry bulb temperature (vertical, green); humidity ration (horizontal, dark blue); relative humidity (curved, red); wet bulb temperature (inclined, light blue); enthalpy (inclined, black); specific volume (inclined, green). At the top of the chart, the humidity is about 30g/kg. Compared to the amount of nitrogen and oxygen – 78% and 21% (by volume) in the atmosphere, this number looks small. Nevertheless, it is the variation of moisture content from 'near zero' to 30 g/kg that plays a significant role in the enormous variety of climate that we experience.
Courtesy: Carrier Corporation.

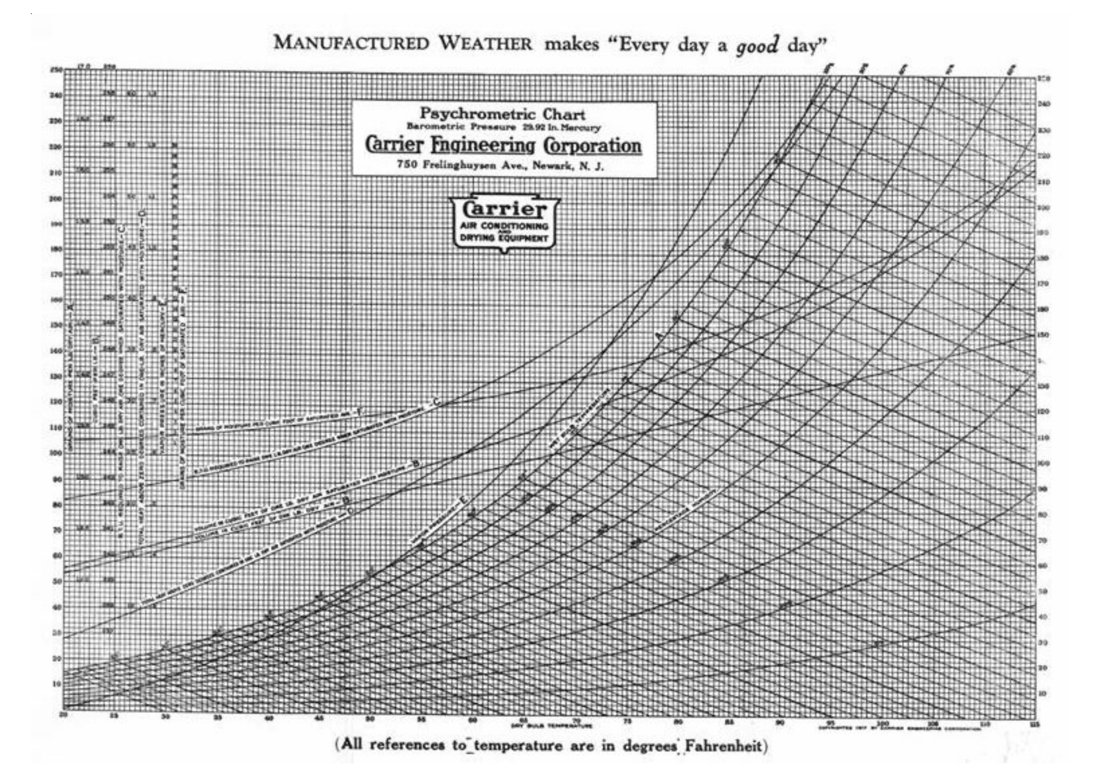



**Figure 2.** Psychrometric chart referenced to in the paper 'Rational Psychrometric Formulae'.
Courtesy: Carrier WHQ, Farmington, CT 06032.

of Improvement in Refrigeration,' which described plans for a new type of machine. Carrier wrote:

*The entire system of electric transmission has been developed from nothing to an enormous industry with relatively simple motors that are high-speed rotative equipment. Industry has gone from low-speed reciprocating steam engines to high-speed rotative turbines. Pumping machinery is rapidly changing from reciprocating types to high-speed rotative pumps for both liquids and gases. Modern power plants have installed high-speed, direct-connected, centrifugal, boiler-feed pumps almost exclusively in replacing the old type of steam-driven reciprocating machines.*

*Refrigeration, though classed among the older mechanical arts, has shown no such material progress. The same improvements* *that have taken place in electrical transmission and in steam machines and pumps must come in refrigerating machines.*

This memorandum was the genesis of the concept of the centrifugal refrigeration machine – way different from the reciprocating chillers then in vogue. It had a direct drive suitable for high speed operation and heat exchangers that were compact, simple, and effective – both performance-wise and cost-wise.

The centrifugal machine is the first major advance in mechanical refrigeration since David Boyle's ammonia compressor in 1872.

The new machine featured a new refrigerant – Dielene, which was non-toxic and had characteristics suitable for with radically improved mechanical equipment along with many other state-of-art components. The machine was tested, installed and commissioned in Carrier's factory itself in May 1922. The first centrifugal machine sold was in 1923. It was still functioning 28 years later.

Even though the installation of the number of machines soared, each one of them was tested thoroughly. Defects were rectified and improvements made. The purging system, i.e., the removal of moisture and contaminants from the machine was vastly improved. The seal mechanism underwent a major design change, essentially and concept-wise; it was separating the two functions of providing a seal and using the thrust on the impeller due to the difference of pressure across the two sides.

It is thus that Carrier introduced the first major advance in mechanical refrigeration since David Boyle designed the original ammonia compressor in 1872. This kind of invention could occur fortuitously and by a team in the natural course of R&D work but the Carrier centrifugal machine was a result of a process that was deliberately initiated and pursued to the ultimate goal of producing a functioning commercial machine.

The sale of machines soared as the market widened to cinema theatres, offices, ships, railroad cars, ice-skating rinks, and to many other applications.

**Introduction of Dielene and Carrene (Freon) Refrigerants**

It has already been noted that the first centrifugal machine came with dielene refrigerant. Later, during the 1930s, it was replaced (in the centrifugals) by methyl chloride (Carrene-1). The latter, in turn made way for Freon-12 (Carrene-2). Carrier's contribution to the research involved in introducing these refrigerants was major.

**The Conduit Weather Master**

A well-known Carrier product of this period was the 'Conduit Weather Master', essentially an Air Handling Unit (AHU) as we call in our country.

This was invented by Carrier to tackle the special problems that skyscrapers were posing – the height and the large number of rooms per floor, which meant, in turn, large risers for conveying the outside (ventilation) air (OA). The solution was obviously to go for high velocity ducting but that entailed high energy consumption for transporting OA. Carrier used its high energy instead to draw room air for recirculation by induction (entrainment). This removed the need for a fan in the room unit. For a schematic diagram and related explanations, see *Box* 3.

**The NACA Project**

Carrier continued making his contributions to the industry in various ways through the War and thereafter. Referring to one of his many achievements, Carrier chose to name one in particular:

*Once, I accomplished the impossible. That is, the task seemed impossible when I first tackled it. And because of its success, high officials in the Air Force told me that World War II was shortened by many months.*

The last major project that Carrier was involved in, was during the war. It was for providing NACA (National Advisory Committee for Aeronautics), a refrigerating system for installation in its wind tunnel at Cleveland, Ohio to simulate freezing high-altitude

**Box 3. Conduit Weather Master**

The standard AHU is in fact a low velocity equipment. This results in increased sizes of the AHUs and several other elements of the air distribution system including ducting. Of particular importance is the OA duct. It is perceived to occupy an unconscionably large space – especially in the shafts of high rise buildings. Conduit Weather Master was the Carrier way of saving space by smaller ducts.

The OA duct looms large (in a low velocity ducting system with a maximum possible air velocity of 10 m/s) but it is in the context of its space requirement in the risers. In reality, it is relatively small compared to the return air flows involved (5 to 15% of total air). The room requires removal of both sensible heat and latent heat load. Moisture removal requires a low supply air temperature (saturated air but at lower dew points) at more or less fixed air flow rate. Sensible heat removal, on the other hand, can be managed more easily since several combinations of DBT and air flow rates will be available as options. Carrier therefore cooled the entire (though small) OA flow only to the necessary (low) dew point – and that too in a remote OA unit. The space required for OA duct is significantly reduced this way. The approach also meant that there would be no condensate disposal problems left to be handled particularly in the room and many other obvious advantages. The high velocity (20 m/s) ducting carrying OA is the ‘Conduit’ in the ‘Conduit Weather Master’.

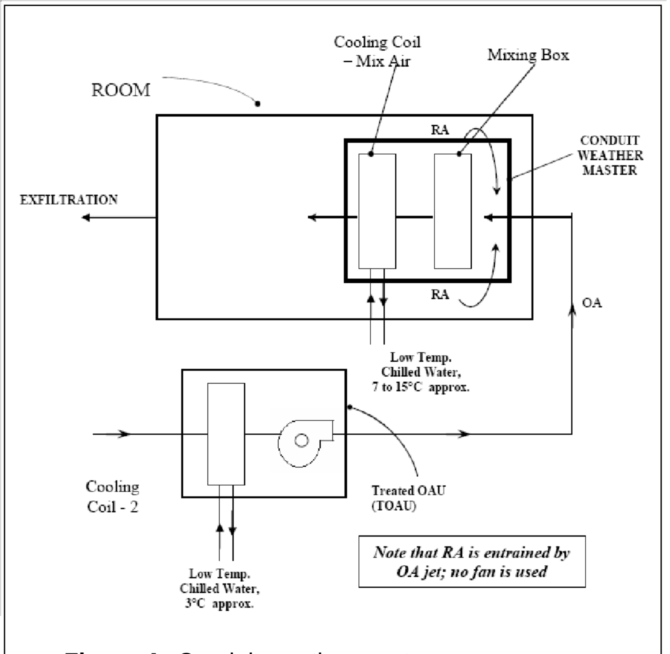



**Figure A**. Conduit weather master.

There were no moving parts in the Conduit Weather Master itself. All external energy required for air circulation was supplied from the fan in the (remote) central station system selected to handle (primary) OA flow.

conditions for testing of prototype planes. 10 million cubic feet of air per minute had to be refrigerated to 67 °F below ‘zero’. This corresponds to a plant capacity of 2,10,000 TR (7,42,000 kW). A big plant indeed – as big as the big plants associated with today’s district cooling plants. The company had to build their own test setup to secure data to validate the design of cooling coils, construct a miniature wind tunnel and carry out tests on cooling coils.

**The Carrier Way of Acting on Concepts, Ideas and Hunches**

Carrier would carry a problem in his head for several years but would not give it up. Probably, the solutions would come in a flash after long periods of deep thinking. But in spite of all that effort, for some reason or other if it turned out that it would after all not be such a commercial success, he would discard it without batting an eyelid. He would say "I fish only for edible fish, and hunt only for edible game – even in the laboratory."

He often postponed action on a problem but never abandoned one that promised to be worthwhile.

Carrier's alert mind would see and capture solutions to a nagging problem in environments in which he was not looking for solutions to those problems. He would be looking for an answer to a problem occupying his mind but would find a solution to some other problem of even greater import. Once, a chemist describing to him the production of 'Freon-12', mentioned the characteristics of a gas obtained in an intermediate step, and stated that there was no intention of producing it except in the industrial process. From the data he got, Carrier believed the gas would be an ideal refrigerant for centrifugal compression, so asked him for the data. They were still written in pencil on worksheets. The chemist had a Photostat of them made for him, and later supplied him with a small sample of the fluid. That became Carrene-2, also known as 'Freon-12.'

Carrier's absorption, when obsessed with a problem, would be total. He was on it, wherever he was – at home, in the bathroom, on the road, while on the train and even to the extent of being oblivious of those talking to him. In fact, the "flash of genius" as some of his colleagues put it, struck him when he was waiting for a train on a railway platform thinking about fog on that foggy evening; the result – the famous Carrier concept of 'the dew point control'.

## The Carrier Way of Selling

Carrier realized that he needed to give a big helping hand to his own colleagues – and the market too – to really sell his 'Apparatus for Treating Air'. Carrier began writing a catalogue in 1905 which was published the following year under the title 'Buffalo Air Washer and Humidifier'. In the catalogue he published data not found in textbooks of the time, defined psychrometric terms, and included a hygrometric chart which, when refined and published in 1911, was to bring him international fame. The reader will appreciate the all-embracing A to Z concept of selling.

Even today the *Carrier System Design Manual* is an integral part of every air conditioning organization.

## Carrier's Concept of Sharing Knowledge

While Carrier was writing the catalogue he saw that the industry needed a handbook from which engineers could get pertinent data on air, and how to control it, without referring to numerous books and obscure articles. It took Carrier eight years to compile the handbook. Buffalo Forge published the first edition in1914 and the fifth edition in 1948. He saw that he had to empower the market to think and accept his ways and concepts. This meant sharing of knowledge – with the entire industry. This is not a widely popular and accepted notion in business and industry.

## Did Carrier Make the HVAC Engineer's Job too Easy?!

Carrier did perhaps spoon-feed HVAC engineers by his work on psychrometrics (and the psychrometric chart); his comprehensive and all-inclusive catalogues, his handbook (the *Carrier System Design Manual*, called the Bible for air conditioning engineers), his contributions to knowledge of air distribution system, sizing, methods and calculations. There is a prevailing opinion among some engineers (the most distinguished of them) that this has – in some measure – bypassed the need for in-depth studies of fundamentals of air conditioning. A working understanding of natural (or passive) cooling methods is becoming increasingly indispensable, because the current standard of comfort (2010 version of ASHRAE Std. 55) applies to naturally conditioned spaces also. HVAC engineers today are not

## Suggested Reading


[1] **Cloud Wampler, *Dr. Willis H. Carrier: Father of Air Conditioning*, Carrier Corporation of Syracuse, New York. The article draws heavily on this source for biographical details as well as his career and achievements.**

[3] **Carrier Corporation – The Great Idea Finder Website – source for some details of Carrier's life, career and achievements.**

[4] **Willis Carrier, *Wikipedia* – source for some details of Carrier's life, career and achievements.**

[5] **M Ingels, *Willis Haviland Carrier: Father of Air Conditioning*, Country Life Press, New York, 1952.**

conversant with the principles and application of natural ventilation and other passive cooling methods. It is in this context that one wonders, if Carrier did indeed make it all too easy for mainstream HVAC practitioners – and thus, deprived them of the opportunity and motivation to acquire an in-depth knowledge of air conditioning.

### Carrier's Legacy

The Magna Carta of air conditioning, the psychrometric chart, the air treatment apparatus, law of constant dew-point depression, dew-point control, centrifugal machine, are all still very much in vogue. Many of them were conceived, implemented and put to beneficial use while Carrier was still young, i.e., more or less a century ago. These epochal events – aside from countless intangible gains that flow from such an eventful and colorful career and life lived to the full, and such an imposing personality, go to make Carrier's legacy.

### Recognition, Honors and Awards

For his contributions to science and industry, Willis Carrier was awarded an honorary doctor of letters from Alfred (NY) University in 1942; was awarded the Frank P Brown Medal in 1942; and was inducted posthumously in the National Inventors Hall of Fame (1985) and the Buffalo Science Museum Hall of Fame (2008).

### The Twilight Years

Carrier lay horizontal 20 hours a day for a period of 3 years on doctor's order because of a heart ailment during the twilight period of his career. Mostly, he was on his back with a pad of papers on his knees, his slide rule close at hand figuring out ways to simplify complex calculations. He passed away in October 1950 a little before his 74th birthday.

**Acknowledgements**

I wish to thank Carrier WHQ for furnishing *Figure* 3 (Psychrometric chart referenced to in the paper 'Rational Psychrometric Formulae'). I wish to extend my grateful thanks to Carrier India for coordinating the inputs from Carrier WHQ. I also thank Prof. Jaywant Arakeri, IISc for the several discussions we had together and his valuable comments and suggestions.

*Address for Correspondence*
R V Simha
Director
Airtron Consulting Engineers Pvt Ltd, No. 502/A, Ist Main
Jayanagar 8th Block
Bangalore 560 070, India.
Email: simha@airtron.in

## Appendix 1. Air Conditioning

The primary need in India is for cooling. North of the Vindhyas, the climate is hot and dry in summer (4 months). which is followed by 4 months of winter and 3–4 months of rainy season. This mixture of seasons is categorized as 'Composite Climate' since this distribution does not fit into any other specific category. Amongst the 3 seasons, air conditioning is required for about 8 months – comprising the summer and monsoon months. Cooling is required all the 8 months of these 2 seasons; besides, moisture (or latent heat) needs to be removed in the 4-month rainy season. In the south, the picture is almost the same (composite climate) in inland areas but, it is necessary to factor warm and humid conditions in coastal areas throughout the year. In this scenario, it is seen that most of the requirement is for cooling and dehumidification in our country. *Figures* 1A and 1B show typical air conditioning processes involved in cooling (and humidification).

In air conditioning the total air in circulation consists of about 90% of return air (re-circulated) the balance being outside air (for ventilation). With outside air being hotter and more humid (meaning higher enthalpy) than in conditioned space, its flow rate is kept to the minimum – this ploy reducing the air conditioning load. The flow diagrams (*Figures* A and B) for the air cycle show the mixture condition. The mixture is cooled – and dehumidified (along the GSHF line right down to the point on saturation line) at which air needs to be supplied in order to extract both the latent heat and the sensible heat from the room at the required rates. This occurs in the Con-

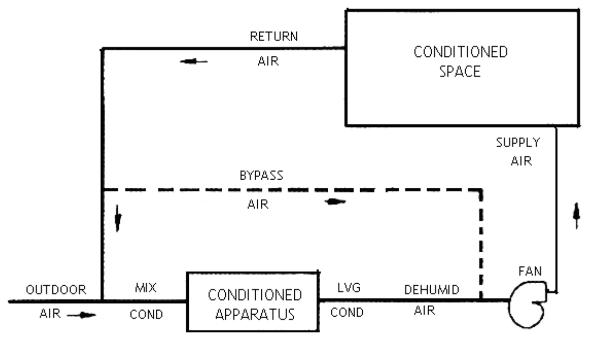



**Figure A.** Basic diagram of the air-conditioning cycle and its elements.

- Mix. Cond – Mixed AIr Conditions
- Lvg. Cond – Leaving Air Conditions
- Deh. Air – Dehumidified Air
- Conditioning Apparatus (same as Air Handling Unit).

Reproduced from Applied Psychrometrics, *Carrier System Design Manual,* Chapter 8.

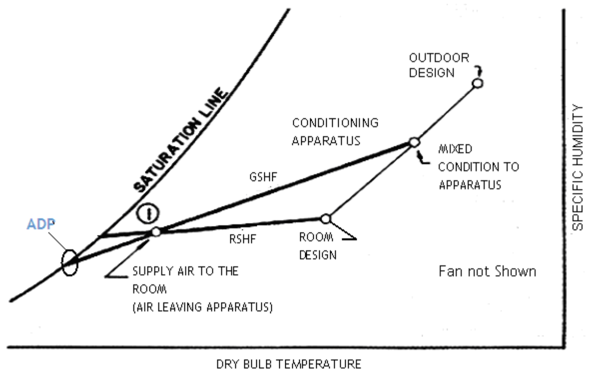



**Figure B.** Air conditioning processes on psychrometric chart.

- ADP – Apparatus Dew Point,
- RSHF – Room Sensible Heat Factor
  (Room sensible heat gain/total room heat gain)
- GSHF – Grand Sensible Heat Factor

Reproduced from Applied Psychrometrics, Chapter 8, *Carrier System Design Manual* and Airtron Bangalore, India.

ditioning Apparatus (cooling coil). The air leaving the cooling coil at a temperature close to ADP is then supplied to the room from which it picks up the room heat gains. A part of the Return Air is expelled to the outside and replaced by an equal quantum of OA. The mixture is then ready to enter the cooling coil.

The cooling coil is a heat exchanger – today typically of (copper) tubes and (aluminum) fins, much like automobile radiators. Typically, a refrigerant or brine (this includes water also) flow is within the tubes, while air flow is without and through fins.

The Air Handling Unit (conditioning apparatus) is the key element of the air cycle. Basic components of the AHU are fan motor set, cooling coil, and modulating face and bypass dampers (for control of air flow through the coil), mixing box with return air and outside air openings. Face and bypass dampers are interlinked so that when the former is opened, the latter is closed and vice-versa. Arrangement provides control of relative humidity. Mixture of outside air and room air is cooled (and dehumidified) along the GSHF line in the cooling coil (not shown in the diagram). Heat from the room (both sensible and latent) is picked up by air entering the room (at point 1) to maintain the room conditions.

In general comfort cooling, typically, the values of the more important state points in the air cycles would be: room:– 24.5°C db, 55% rh, 14.9°C dp; ADP = 13.3°C (db = 13.3°C , wb = 13.3°C , rh = 100% – since the air is saturated and Ws = 13.3 g/kg); air leaving the cooling coil = 14.1°C db. The OA requirements would be 10% approximately. That the supply air dew point should be below room DP (14.9°C) was generally known to everybody, but nobody knew what its value should be.

## Appendix 2. Sackett–Wilhelms Plant And Psychrometric Chart

Below are some calculations which show how a psychrometric chart can be used on a project like 'Sackett–Wilhelms Lithography and Publishing Company of Brooklyn, New York'.

The most authentic and widely used psychrometric charts today are the ASHRAE charts. A psychrometric chart graphically represents the thermodynamic properties of moist air. The choice of coordinates for a psychrometric chart is arbitrary. A chart with coordinates of DBT and humidity ratio provides convenient graphical solutions of many moist air problems with a minimum of thermodynamic approximations. There are seven charts as listed below.

| | | |
|---|---|---|
| Charts 1, 5, 6, 7 | Normal temperature | 0 to 50 °C |
| Chart 2 | Low temperature | 40 to 10 °C |
| Chart 3 | High temperature | 10 to 120 °C |
| Chart 4 | Very high temperature | 100 to 200 °C |

Chart 1 is for sea level while, charts 5, 6 and 7 cover 750 m, 1500 m and 2250 m respectively.

Two valid parameters serve to fix a state point on a psychrometric chart; all the rest of the parameters can be read-off from the chart. If two state points are plotted on the chart, the line joining them is called the 'Conditioned Line'. The difference between the properties at the two state-points like dry bulb temperatures and wet bulb temperatures can be read off from the chart. Various air conditioning processes like sensible cooling, latent cooling, and resulting changes in enthalpies can be read-off on the chart. These in turn will enable the engineer to read-off, calculate and determine the results of these various processes and help him visualize them.

Many of the important terms and equations used in air conditioning are defined in *Box* 1 and can now be applied with reference to the Sackett–Wilhelms project:

ERSH (Effective Room Sensible Heat) = 1.23Q ($t_{rm} - t_{adp}$) × (1-BF)
ERLH (Effective Room Latent Heat) = 3.010Q ($w_{rm} - w_{adp}$) × (1-BF)
ERTH (Effective Room Total Heat) = 1.2Q ($h_e - h_l$) x (1-BF)

where, $Q$ = airflow rate – l/s; $t_{rm}$ = room temperature, °C; $w_{rm}$ = Room humidity ratio, kg (water)/kg (dry air); $h_e$ – enthalpy of entering air, kJ/kg (dry air); $h_l$ – enthalpy of leaving air, kJ/kg (dry air) as applicable to cooling coils.

The equation for ADP (Apparatus Dew Point) is

$$\text{ADP} = \frac{1.23(t_{\text{rm}} - t_{\text{adp}})}{1.23(t_{\text{rm}} - t_{\text{adp}}) + 3.010(w_{\text{rm}} - w_{\text{adp}})}$$

There are apparently two unknowns in this equation viz., $t_{adp}$ and $w_{sadp}$. However, every value of dew point temperature corresponds to a value of humidity ratio. Accordingly, the value of $w_{adp}$ can be read-off from a table of properties of moist air once the ADP is known. The above equation has to be solved for ADP by iteration. From the cooling load calculations, SHF (Sensible Heat Factor) is known. Enter with an assumed value of $t_{adp}$ and calculate SHF. The calculated SHF may not be equal to the assumed SHF. Iterate the calculation till agreement between the two SHFs is reached.

Another method of finding ADP is to locate the room condition, draw a line through it to represent the SHF. The slope of the line can be obtained from the protractor provided on the ASHRAE psychrometric chart. The SHF line can be transferred from the protractor to the state point representing the room conditions using a pair of set squares. The ADP can be located at the intersection of the SHF line with the saturation curve (see *Figure* A). Solving the equation for ADP is more accurate. In most applications a software is used to do such calculations; the geometric approach is useful to develop a physical understanding of the processes involved.

The data relevant to this project are listed below:

Room: 27°C db / 55% rh / 20.37°C wb 17.19°C dp / 12.282 g/kg HR
SHF required : 0.820
BF : 0.1

Referring to a table showing a relation between SHF and ADP for given room conditions, find the ADP value of 15.6.

In conventional comfort air conditioning today, the cooling coils use copper tubes and aluminium fins with refrigerant in tubes and air passing over them and through the fins. Refrigerants would be from later generations – like R22, R134A, 404A and 407C for example, in case of DX systems.

In Carrier's days, there were no such coils and no such refrigerants either, $NH_3$ was the common refrigerant. $NH_3$ would cool the brine in a remote brine chilling plant and air would pass through a high pressure spray of the chilled brine (spray equipment/air washers). This would extract the heat from the air. Accordingly, chilled water/brine plants were the order of the day. This is shown in *Figure* A but a sketch showing the use of a coil in lieu of the spray in the chilled water loop is also included separately.

*Figure* B shows the state-points and condition lines marked on ASHRAE Chart No.1. These values can be compared with corresponding values for the example cited for general comfort cooling on page 136 viz., 24.5°C db, 55% rh, 14.9°C dp; ADP 13.3°C (db = 13.3°C, wb = 13.3°C, rh = 100%). Note in particular that the small difference (0.21°C) between dew-point depressions of 9.81°C (27°C–17.19°C) and 9.6°C (24.5°C–14.9°C) in the case of those calculations and the calculations made for general comfort cooling respectively for the same relative humidity of 55%, illustrates the law of constant dew-point depression also.

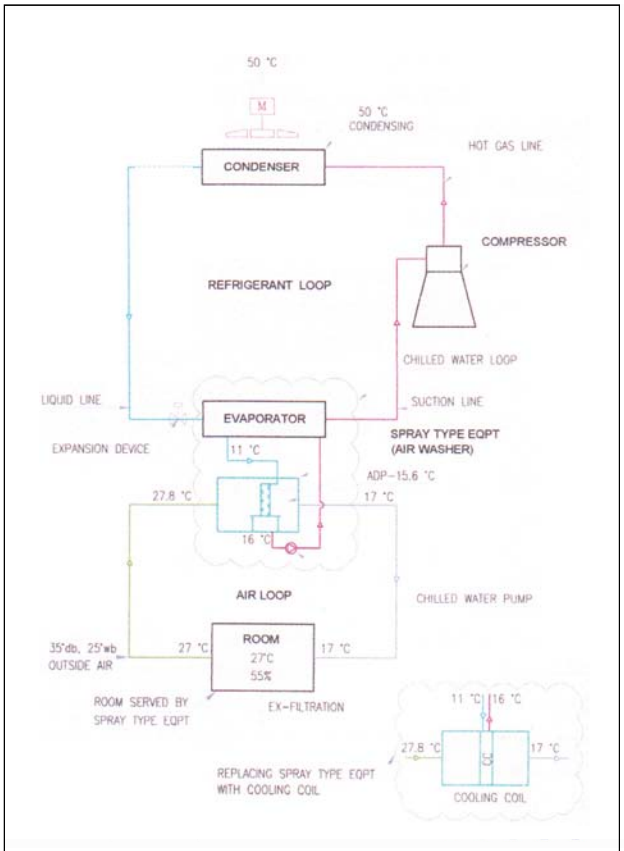



**Figure A.** Schematic flow diagram for Sackett–Wilhelms plant with spray system. Alternate system with cooling coil in the chilled water loop is also shown (separately).

**Figure B.** Part view of ASHRAE Psychrometric Chart No. 1 showing state-point and condition lines.