Dr. Willis H. Carrier (1876 - 1950)

Remembering Dr. Willis Carrier

On the occasion of 100 years of publication of *Rational Psychrometric Formulæ - Magna Carta of Psychrometrics*

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By Way of Introduction

Born in 1876, graduated in 1901, joined a heating and ventilating company in 1901, got an R&D Lab, created and headed it in 1902, solved a quality problem in a lithography and printing press in 1902 (this was the birth of air conditioning) and defined what air conditioning is all about, developed the psychrometric chart (1904) – which is still being used in its several *avatars,* discovered the Law of Constant Dew-point (1906), set up a subsidiary of his employer company to engineer and market air conditioning systems (early 1908), presented the landmark paper *Rational Psychrometric Formulae* (also called the *Magna Carta of Psychrometrics),* established a new company for air conditioning (1915), kept nurturing the industry as it came of age, invented and patented the centrifugal refrigeration machine (1921), spawned a number of ancillaries for the air conditioning industry with several of them growing into international brands and still going strong in the global HVAC market.

The reader could be excused if he wonders who this young man is, hardly 30-35 years of age with such a long list of achievements. It has to be Dr. Willis H Carrier, known by several honorifics – *Engineer and Inventor, Scientist and Inventor, Founder of the Air Conditioning Industry… Father of Air Conditioning.* Of these and many other honorifics, the one he is most readily and widely identified with is "The Father of Air Conditioning". Indeed he has often been compared with such celebrities as Edison, Ford and Bell and Wright Brothers.

Dr. Carrier's Forebears

Willis Carrier was born in the year 1876 in a farm on the western parts of New York State. The first Carrier in America was a Thomas, who arrived in Massachusetts around 1663. He was a political refugee from England, and assumed the name Carrier on coming to America.

Thomas Carrier's wife Martha Allen was her husband's equal in all except in longevity. She was "plain and outspoken in speech, had a remarkable strength of mind, a keen sense of justice and a sharp tongue". After standing up against the Andover (a town in Essex, Massachusetts) town fathers in a boundary dispute, she was accused of being a witch and was convicted and hanged in Salem's Gallows hills. The Carriers eventually moved over (along with a settlers' group) to New York State. They purchased a farm which became the birth place and childhood home of Willis Carrier. Willis father was Duane Carrier. He settled down to farming after trying his hand at various other occupations. Willis mother was Haviland, whose forebears had settled in New England in 17th century.

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, he was tackling the problem of a perpetual motion machine. He could not grasp the meaning of fraction; 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-

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hour, she educated me." Carrier used to say that whatever talents he had in mechanics and mathematics, he inherited from his mother. And his mother died when he was 11 years old.

Carrier Works His Way Through College

Carrier had a robust and athletic personality. He finished school and entered Cornell University. He worked his way by distributing milk, driving home and sometimes walking a mile across the fields to school. He was active in several sports - basketball, skating, swimming and boxing. He worked hard and earned through scholarships and teaching and by making money on odd jobs – mowing lawns, tending furnaces, 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 students' co-ops in the United States. Carrier received a degree in mechanical engineering from Cornell University in 1901.

Carrier was not a conformist even during his school and college days. He was an independent thinker. He followed his mother's advice – "Figure out things for yourself". No reader can miss what Carrier owed to his mother from even amongst the host of his truly remarkable forebears.

Young Carrier Pioneers the Discipline of Air Conditioning

Dr. Carrier did not invent air conditioning, nor did he coin the term *"Air Conditioning"* or install the first air conditioning plant. Heating, humidifying, cooling and ventilation were all being done - even though not designed on any scientific and engineering basis but by experience, judgment and thumb rules. There were applications which called for cooling and dehumidifying. Cooling? – yes; but dehumidification – they had no clue. This was the situation at that time. As for coining the term, the credit goes 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 rules of thumb 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 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 in Buffalo Forge Company in 1901. The company was involved in heating, drying and forced draft systems. At the end of just six months, Carrier was presenting a paper at the company's annual meeting, 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. The lab that he founded later became an industrial laboratory – the first R&D Lab in the HVAC industry. He was just 25.

Carrier had already discovered that except for physical and thermal properties of steam and air, no other data was available. He carried out tests, derived equations and completed calculations.

World's First Scientific Air Conditioning System - 1906

The problem which confronted Carrier related to control of humidity in the plant of Sackett-Wilhelms Lithography and Publishing Company of Brooklyn, New York. Printing was troubled 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. The problem landed in Carrier's lap. It did not occur to him that here was a problem that could challenge his ingenuity or that finding a solution would be beyond his capabilities.

Air Conditioning Defined

From out of the hard earned knowledge and experience gained while solving the above problem, 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 through 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 connected to a refrigeration machine. The total installed capacity could have been around 55 TR (195 kW).

On this discovery he based the design of an automatic control system for which he filed a patent claim in 1907. He was thereby recognized as the inventor of Dew-point Control.

Rational Psychrometric Formulae – *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 - Magna Carta of Psychrometrics"*. 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 merely deduced from simultaneous readings of dry bulb, wet bulb and dew-point temperatures was over.

The following principles underline the entire theory of the evaporative method of moisture determination, as well as of air conditioning:

A. 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.

B. 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.

C. 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; i.e. the true wet bulb temperature of air is identical with is temperature of adiabatic saturation.

From these three fundamental principles, a fourth was deduced:

D. 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, providing the total heat of the air is constant.

The Impact of 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 (1904) was reproduced in engineering college and school textbooks that began to include air conditioning as a subject to be covered by their students. His *Formulae* were 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 be truly said that the industry which he and his colleagues had founded just a few years earlier (1906) had now come of age.

Today's Psychrometric Chart Compared With the Chart *Circa* 1904-1906

It will be seen from *Figures 1* and *2* that the psychrometric charts currently in use are not significantly different from the chart *(Figure 3)* referenced in the paper.

Dry bulb temperature lines are straight, not precisely parallel to each other, and inclined slightly from the vertical position. Thermodynamic wet bulb temperature lines are oblique and in a slightly different direction from enthalpy lines. They are straight but are not precisely parallel to each other. The enthalpy lines however are oblique lines drawn across the chart precisely parallel

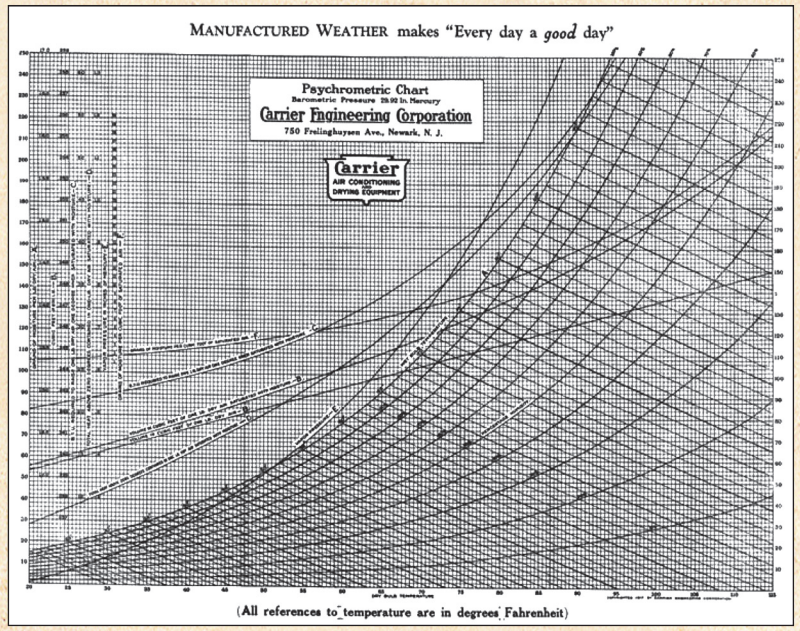

Figure 1: Psychrometric chart referenced to in the paper "Rational Psychrometric Formulae"

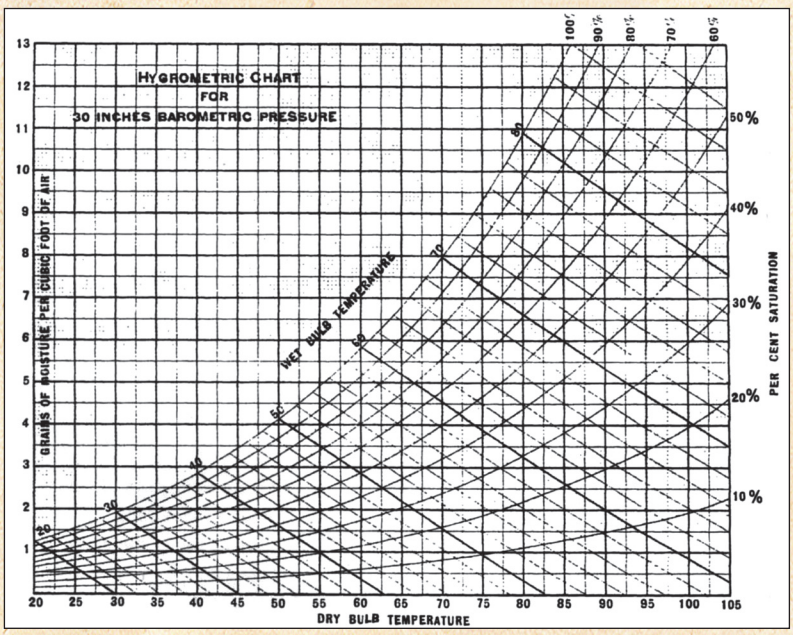

Figure 2: This chart was in use as far back as in 1904

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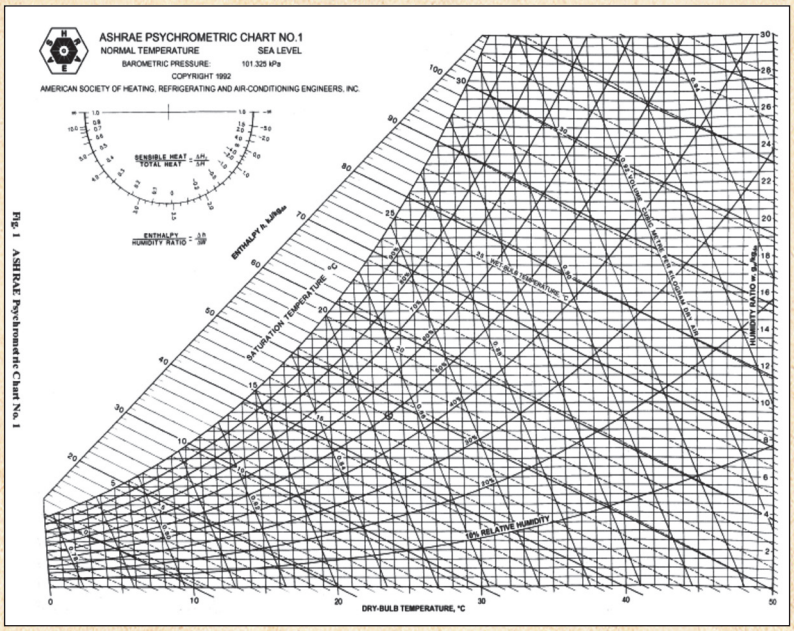

Figure 3: A typical psychrometric chart currently in use

to each other.

At the top of the chart, the humidity ratio is seen to be about 30 g/kg. Compared with the strength of nitrogen and oxygen – 78% and 21% (by volume) in the atmosphere – this looks pretty small. Nevertheless, it is the variation of moisture content from near zero to 30 g/kg. But as we all know, humidity does play a significant role in the enormous variety of climates that we experience from place to place, season to season and day to day.

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 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.

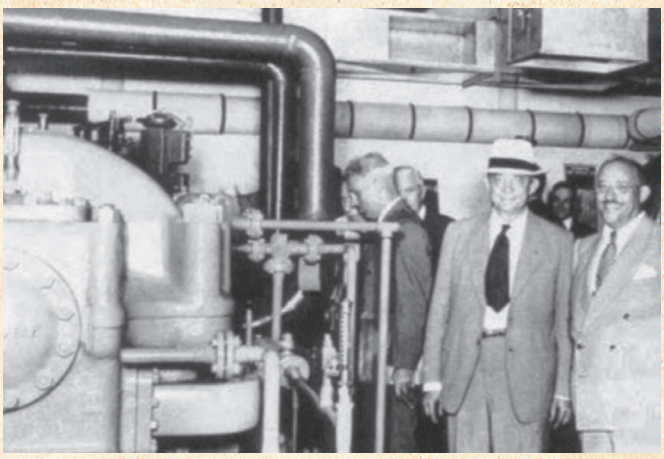

Figure 4: With the centrifugal machine - Dr. Carrier is seen in the middle (in hat and tie)

The new machine featured a new refrigerant – Dielene, which was non-toxic and had characteristics adaptable for operation 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 running 28 years later.

As the number of machines installed soared, every one of them was tested thoroughly as if in a lab. 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 Dr. 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 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). Dr.

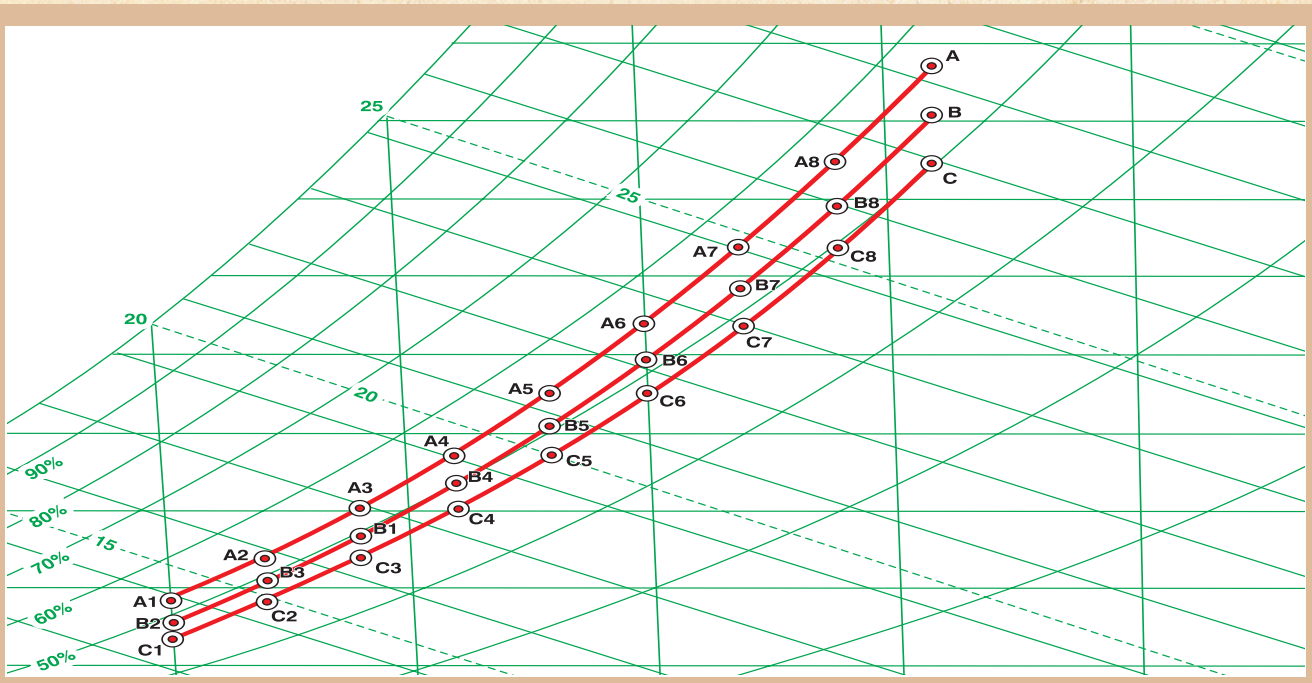

Figure 4: DBT vs constant DPD and RH lines

Description	A				B				C			
	DB°C	DP°C	RH%	DP Depression	DB°C	DP°C	RH%	DP Depression	DB°C	DP°C	RH%	DP Depression
Ref. Pt	24	14	53.55	10	24	13	50.00	11.06	24	12	46.99	12
Max.	36	26	56.56	10	36	25	53.11	11.06	36	24	50.20	12
Min.	20	10	52.50	10	20	9	48.89	11.06	20	8	45.58	e12
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 1: Study of deviation between DPD and RH lines

Comments on Application of Law of Constant Dew-point Depression:

Table 1 and *Figure 4* above, show the deviation of relative humidity from the law of constant dew-point depression for a DB-24°C/RH-53.55%, DB-24°C/RH-50%, and DB-24° C/RH-46.9%. It will be seen that at any given constant dew-point depression, the deviation is under 5% over a dry bulb temperature variation of 16°C from 20°C to 36°C (note also that the error increases with DB temperature as well as DP depression). For most engineering purposes, this error is negligible and therefore, a dew-point depression line can denote the corresponding RH value. In most air conditioning apparatus handling cooling and dehumidification processes, the temperature of air leaving the apparatus will be close to the dew-point. This is especially so in the case of spray equipment (air washers). Accordingly, the difference between the room dry bulb temperature and the supply air temperature can be regarded as identical to the dew-point depression. This way a relative humidity can be measured by sensing two temperatures only; no humidity measurement is involved. On rising room RH, the requirement is that the dew-point depression should be increased. This can only be done either by raising the room dry bulb temperature or by lowering the leaving air temperature (dew-point temperature or supply air temperature).

In practice, the dew-point temperature is kept constant and as the room dry bulb temperature falls (during part load or rainy weather conditions), the supply air is heated (commonly called "reheat") to restore the room temperature and thus maintain the dew-point depression. This is what is known as "Dew-point Control". This simple scheme takes care of most comfort cooling applications as well as many industrial and manufacturing requirements because they do not involve either high latent heat loads or any significantly close RH control. If the latent heat loads are large and the dew-point needs to be lowered, the supply air temperature is reset correspondingly to a lower value – by room humidity sensor, automatically, if so desired.

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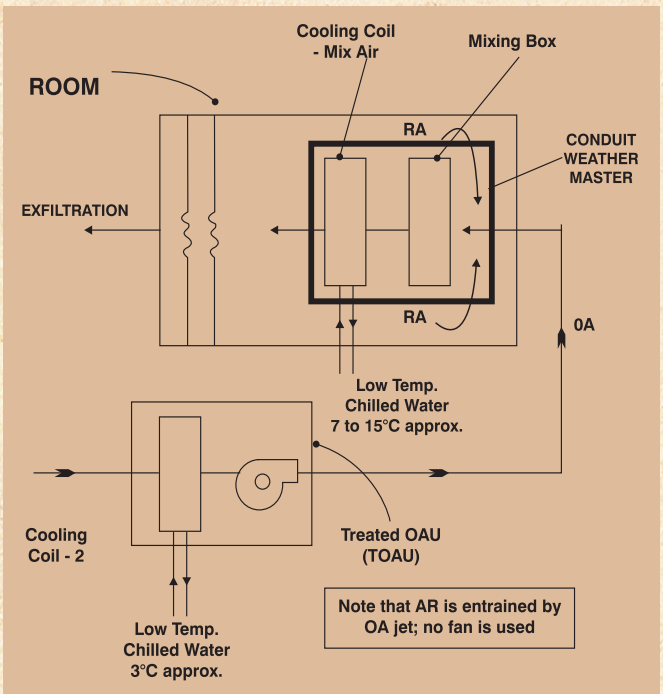
Carrier's contribution to the research involved in introducing these refrigerants was major.

The Conduit Weather Master

A well known Carrier product of this period was the Conduit Weather Master, essentially an AHU. This was invented by Dr. 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 obviously was 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 did away with the need for a fan in the room unit. For a schematic diagram, please see *Figure 5*.



The OA duct looms large (in a low velocity ducting system) but this 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%). 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 DB temperature and air flow rates will be available as options. Carrier therefore cooled the entire OA flow and only that to the necessary (low) dew-point and that, in a remote OA unit. This also meant that there would be no condensate disposal problems left to be handled particularly in the room – with many other obvious advantages. The high velocity ducting carrying OA is the "Conduit" in the "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.

Figure 5: Conduit Weather Master

The NACA Project

Dr. 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 Dr. Carrier was involved in was also during the war. It was for providing National Advisory Committee for Aeronautics (NACA) a refrigerating system for installation in its wind tunnel at Cleveland, Ohio to simulate freezing high-altitude conditions for testing of prototype planes. 10 million cubic feet of air per minute had to be refrigerated to 67°F. This corresponds to a plant capacity of 2,10,000 TR (7,42,000 kW) based on evaporating and condensing temperatures that characterize air conditioning. A big plant indeed - as big as the plants associated with today's district cooling projects. 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. Centrifugal compressor machines were designed for Freon-12. Fourteen centrifugal machines of 15000 HP each were selected to maintain conditions of air simulating altitudes up to 30000 feet, had to cool 50 pounds of gasoline per minute for the units, cool the makeup air to the tunnel, produce chilled water and brine and refrigerate the coils for an icing tunnel located nearby when the wind tunnel was shut down. The work was finally completed and ready for a formal run-in test on time.

The Absent Minded Genius

On occasions, Carrier would get so immersed in work that he lost count of time. Breakfast, lunch, etc. would pass him by.

After being lost in the study for the best part of the day in sorting out the problem being faced on a plant, he remarked that it must be time for breakfast. Much to his surprise he learned that it was lunch time and that he had missed breakfast completely. On another occasion, during an inspection trip to Pennsylvania, he arrived with a large suitcase in which he had packed only a handkerchief. Another time Carrier and Murphy visited a New England mill, looked over the system, and then went to a restaurant for lunch. All through the meal Carrier drew diagrams on the tablecloth. The waitress would serve him one course, wait and wait for him to eat it, then remove the untouched food and serve the next course. Carrier left the dining room without realizing that he had eaten no food.

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 up. Probably the solutions come in a flash but he did not mind waiting. A flash would be a precursor to long periods of penetrating thinking. But in spite of all the efforts, for some reason or the other, if it turned out that it is not after all going to 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."

Dr. Carrier's alert mind would see and capture solutions to a nagging problem in environments in which he was not looking for solutions. 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 figures he got, Dr. Carrier believed the gas would be an ideal refrigerant for centrifugal compression, so he asked for the data. It was written in pencil on work sheets. The chemist had a photostat of the data made for him, and later supplied him with a small sample of the fluid. That was the beginning of Carrene-2.

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, in 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; result – the famous Carrier concept of 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.

Dr. 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.

Did Dr. Carrier Make the HVAC Engineer's Job Too Easy?

Carrier did perhaps spoon feed HVAC engineers through his work on psychrometrics and the psychrometric chart, his comprehensive and all-inclusive catalogues, his handbooks *(The Carrier System Design Manual,* the Bible for air conditioning engineers), his contributions to the knowledge of air distribution system, sizing, methods and calculations. There is a prevailing opinion that this has – in some measure – bypassed the need for in-depth studies of the fundamentals of air conditioning. A working understanding of Natural (or Passive) Cooling Methods is becoming increasingly indispensible, because the current standard of comfort (2010 version of *ASHRAE Standard 55)* applies to Naturally Conditioned spaces also. HVAC engineers today are not conversant with the principles and application of Natural Ventilation and other Passive Cooling methods. It is in this context that one wonders if Dr. Carrier did indeed make it all too easy for mainstream HVAC practitioners – and thus, deprived them of the opportunity and motivation to acquire in-depth knowledge.

The 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 alive and in vogue. Many of them were conceived, implemented and put to beneficial use while Dr. 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 in full and such an imposing personality, go to make Dr. 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

Dr. Carrier stayed horizontal 20 hours a day for a period of 3 years on his doctor's order because of a heart ailment during the end 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 2 - Psychrometric chart referred to in the paper Rational Psychrometric Formulae.* Carrier India has been extremely helpful in coordinating the inputs from Carrier WHQ. I wish to extend my grateful thanks. I also thank Prof. Jaywant Arakeri (Department of Mechanical Engineering, Indian Institute Of Science, Bangalore) for the several discussions we had together and his valuable comments and suggestions.

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

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