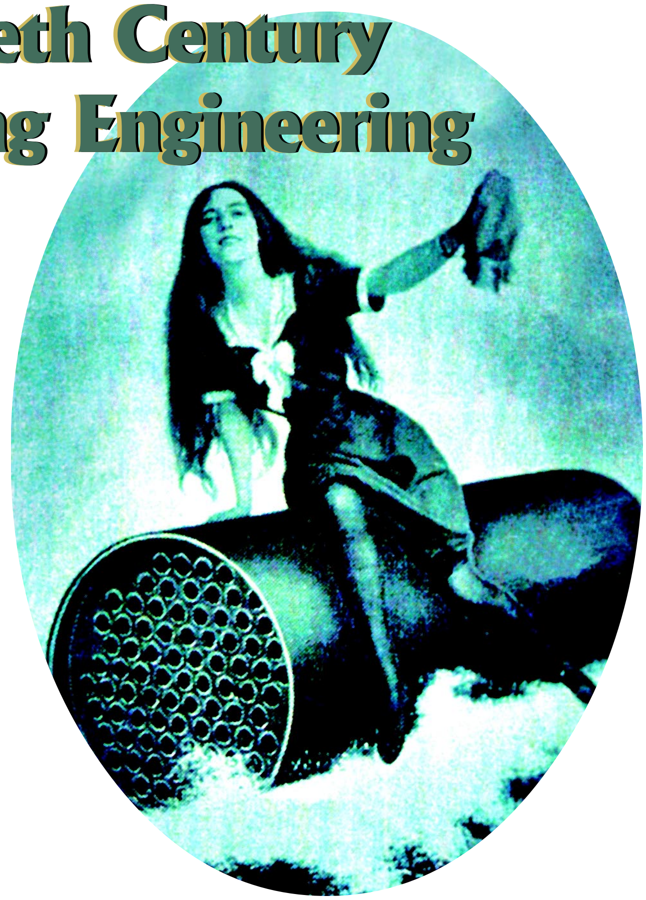
Early Twentieth Century Air-Conditioning Engineering



The First Century of Air Conditioning

This is the fourth article in our special series to commemorate a century of innovation in the HVAC&R arts and sciences.

By Bernard Nagengast
Member ASHRAE

"The practical application of mechanical refrigeration to air cooling for the purposes of personal comfort, no doubt has a field, ... and the day is at hand, or soon will be, when the modern office building, factory, church, theater and even residence will be incomplete without a mechanical air cooling plant."[1] That prediction, made on the occasion of the World's Fair in 1904 by the editors of the trade journal *Ice and Refrigeration*, would see full realization by the end of the new century.

Previous articles in this series on the history of air conditioning have shown that artificial cooling by mechanical means existed prior to 1900. Nineteenth century cooling attempts were the stepping stones to the perfection of mechanical air-conditioning systems and that perfection was reached in the twentieth century. What was an expensive and problematic curiosity evolved into the reliable necessity we have come to know and love: comfort air conditioning.

As the twentieth century approached, several themes set the stage for what was to be an air-conditioned century. Those themes were: commercialization of the mechanical refrigeration industry, introduction of fan-powered heating and ventilating systems into large buildings and most importantly, the combining of science and engineering leading to "scientific air conditioning."

This article focuses on early twentieth century developments in air conditioning engineering that made modern comfort cooling systems possible.

At the Dawn of the New Century

Fan-forced heating systems had developed during the last half of the nineteenth century. Schemes to use the fan system for comfort cooling also appeared. However, use of cold water or evaporative cooling placed a limit on the amount of comfort that could be obtained. A means of drastically cooling air mechanically did not exist until artificial refrigeration was invented.

Vapor compression refrigeration had been proposed in 1805, a working model had been constructed about 1834, and more extensive experiments had been conducted in the early 1850s. In the U.S., demand for reliable cooling for brewing and later for ice making led to the establishment of numerous manufacturing and engineering firms that could design, manufacture and install complete refrigeration systems. This business was well established by 1900. These firms were able to provide a mechanical cooling system just as easily for air cooling as they were for ice making.

Heating systems were also rapidly evolving in the U.S. One method of heating, the so-called hot blast or fan system, was adaptable to building cooling. The hot blast system, also called the plenum system, used a blower fan to force air over a steam- or water-heated surface, distributing the air through ducts to rooms in large buildings. Normally these systems, using 100% outside air, furnished part of the total heating load. Cast-iron radiators, placed at the perimeter of the building, carried the remainder of the load.

As in mechanical refrigeration, a host of manufacturing engineers had arisen to provide complete fan systems. The heating surface in these systems could be provided with refriger-

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ated brine in summer. Fan systems were also being equipped with air washers for filtering and humidifying by the 1890s. Air washers too could be adapted for cooling purposes.

Air-Conditioning Science

Cooling systems proposed or constructed before the 1890s were really hit or miss approaches: the air was at least cooled and sometimes dried. But there was little understanding of the science involved in these processes.

Cooling needed to be approached on a scientific basis to determine how to size equipment, how to cool air to a given temperature, and more importantly, how to remove moisture from air for a desired result in relative humidity.

A genuine scientific approach to cooling originated in Germany. German heating engineers had been refining and applying the heating engineering methods of Eugen Péclet of France. Hermann Rietschel (*Figure 1*), professor at the Berlin Royal Institute of Technology, published the first of many editions of his "Guide to calculating and design of ventilating and heating installations" in 1894. Rietschel presented the science of heating and ventilating in a clear and simplified manner so it would be useful for the designer and contractor.

Significantly, Rietschel had included a chapter on room cooling in his book.[2] For the first time, the rudiments of the engineering science of air conditioning were introduced. Rietschel discussed these pertinent points:

- For calculating heat gain, the highest normally expected outdoor ambient temperature should be used, and the exposure of the outside building walls face must be considered.
- As air is heated it becomes relatively drier, and conversely, as air is cooled, it becomes more dense and relatively more wet. When air is cooled below its dew point, it becomes saturated and water will condense out. Normally, refrigeration systems use very cold heat exchangers that reduce the absolute humidity to a low level. However this cold but saturated air would result in uncomfortable conditions were it to be used for comfort cooling. It is then necessary to mix the cold, saturated air with warmer outdoor air to raise its temperature, but lower its relative humidity.
- The normal heating practice of using 100% outside air would result in a very high cooling system operating cost, because of the latent heat removal encountered in moisture reduction. Therefore, recirculation of part of the room air is important. Supply ducts should introduce cooled air far away enough from the room occupants so that the air is thoroughly diffused.
- An air washer can be used to dehumidify air if the water temperature is sufficiently low. The washed, cooled air can be mixed with recirculated room air and then introduced directly into the room.
- To calculate the size of a refrigerating system for air cooling, it is necessary to determine the load that includes wall heat gains, heat from occupants and lighting.
- Only part of the supply air should be cooled to saturation. Some supply air can be bypassed around the cooling coil, mixed with the cooled air of low absolute humidity resulting in an air supply of lower relative humidity.
- A series of formulas was introduced to determine the temperature to which the air must be cooled to remove a given weight of moisture, to determine the amount of latent and sensible heat that must be removed, and to determine the surface area of the cooling coil. Formulas are included for calculation of the amount of air to be circulated.
- An example of a room cooling problem was given followed by a step-by-step method of calculation.

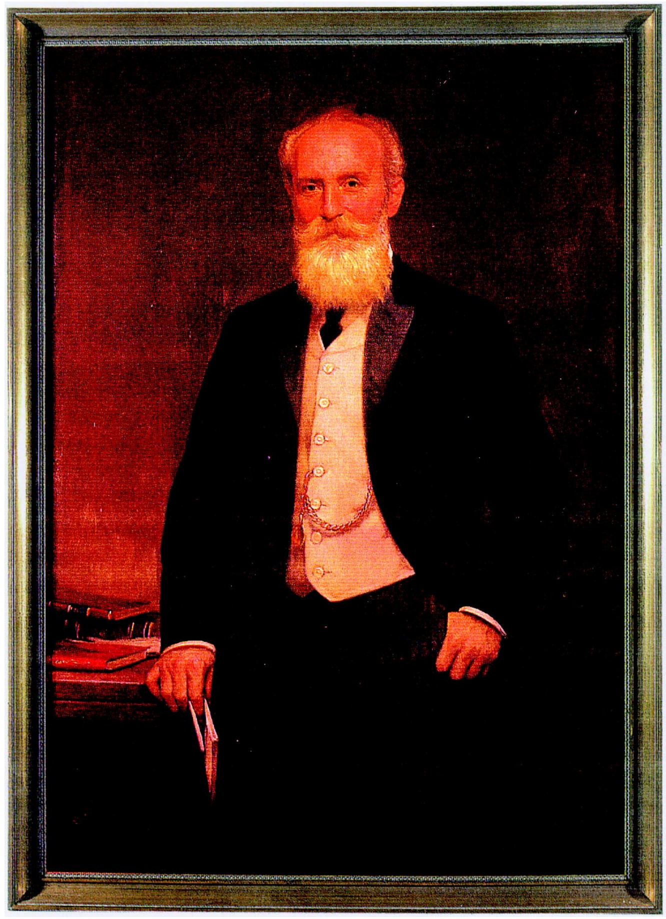

Figure 1: Professor Hermann Rietschel outlined the basis of an engineered approach to comfort cooling in his textbook published in 1894. From Usemann, K. 1993. **Entwicklung von Heizungs- und Lüftungstechnik zur Wissenschaft.**

One of the earliest extensive discussions of comfort air cooling in the U.S. that addressed the need for dehumidification as well as temperature reduction appeared in 1893 in the trade journal *Heating and Ventilation*. The author, Leicester Allen, illustrated the construction of an air cooler that dried the incoming air with a desiccant before cooling it.[3]

Professor Rietschel's scientific approach to cooling was introduced to U.S. engineers by Hermann Eisert, who presented a paper titled "The cooling of closed rooms" at the 1896 meeting of The American Society of Heating and Ventilating Engineers (ASHVE). Alfred Wolff, (*Figure 2*) the leading H&V engineer at the turn of the century, was the first to successfully apply many of Rietschel's principles in the cooling systems he designed for the Cornell Medical College in 1899, the New York Stock Exchange in 1901 and the Hanover National Bank in 1903. The stock exchange job incorporated a most venturesome approach: a 300-ton (1056 kW) co-generation system that provided free cooling. Wolff had expressed his conviction to the Stock Exchange's architect George Post:

"What this means in comfort, in ability to transact business, the health and well-being of the members, can scarcely be realized by a mere recital of ... figures, but must be experienced to be thoroughly appreciated. ... If the refrigerating plant is instituted for the boardroom and the entering air is cooled ... and the percentage of moisture lowered, the result will be that this room will be superior in atmospheric conditions to anything that exists elsewhere. It will mark a new era in the comforts of habitation."[4]

Wolff's boldness was remarkable. No one had ever designed such a large cooling system, used a co-generation approach and put it where the entire world could see it. A stock exchange official had remarked that if the system didn't work, Wolff had better buy a one-way ticket out of New York. But the system did work, and remained in operation for 20 years. Wolff's success proved that mechanical comfort cooling, even on a large scale, was feasible.

Alfred Wolff was not the only U.S. engineer proposing and designing cooling systems as the new century dawned. Others took a calculated approach to comfort cooling as well.

For example, St. Louis refrigeration engineer Alfred Siebert proposed comfort cooling, recognizing the need for reducing the humidity of the air by cooling it to saturation, then reheating it to the desired temperature and relative humidity conditions. Siebert showed calculation examples in an article published in 1897.[5] Siebert also received three U.S. patents for comfort cooling devices, and his first patent issued in 1902 mentions humidity control.[6]

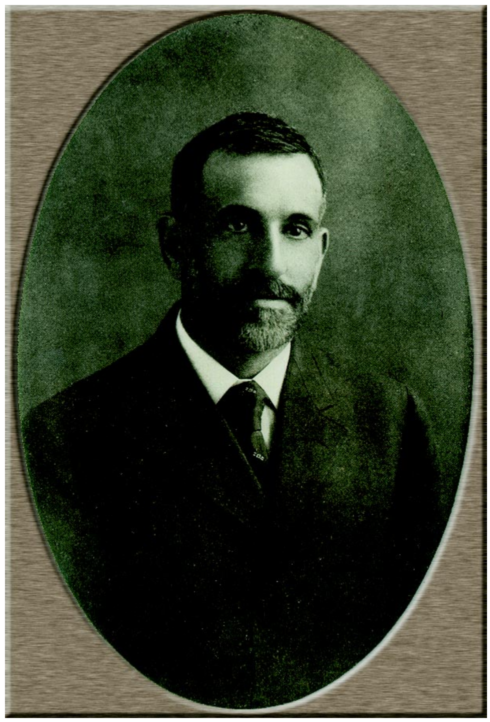

Figure 2: Consulting engineer Alfred Wolff designed a number of successful comfort cooling systems at the turn of the century. From the Robert Wolff Family.

The Public Debut of Comfort Cooling

Sometime prior to 1903, refrigeration engineer Gardner T. Voorhees had cooled his Boston offices for many years. Voorhees was initially in charge of the refrigeration plans for the Louisiana Purchase Exposition, the St. Louis World's Fair of 1904–1905. Voorhees proposed an ambitious program to comfort-cool the fair's refrigeration bureau office to demonstrate the usefulness of comfort cooling and to entice commercial participants to hook up to the fair's central refrigeration plant for air cooling purposes.[7] It seems that the fair administration got cold feet, and Voorhees later said: "In my opinion many practical uses of refrigeration were put back 25 years or more by the action of the St. Louis World's Fair Officials in breaking their contracts... ."[8]

Although Voorhees' dream of cooling the many fair restaurants, exhibits and theaters was not realized, fair goers were treated to one air-conditioned building sponsored by the State of Missouri. The edifice had a comfort-cooled rotunda and 1,000 seat auditorium. Some 35,000 cfm (16 520 L/s) of partially recirculated air, cooled by direct expansion, was delivered through mid-height wall registers.[9] This one installation, the public debut of air conditioning, introduced thousands of fair visitors to comfort cooling.

There were some other mechanically refrigerated comfort-cooling systems installed in the first decade of the new century. Many further extended public exposure to the benefits of summer indoor climate control. Some notable installations were:

• The St. Nicholas Garden in New York was cooled in summer by circulating air under a temporary floor over the ice skating rink. The system, installed before 1901, was kept frozen by 9 miles (14.5 km) of direct expansion ammonia piping.[10]

• In 1906, a cooling plant was installed to cool wards of the Boston Floating Hospital. However, the size of the cooling plant was inadequate. New York consulting engineers Westerberg & Williams were hired to redesign the system in 1907. The new system maintained a design condition of 68°F to 70°F (20°C to 21°C) indoor temperature at a relative humidity of 50% at outdoor design conditions of 88°F (31°C) and 85% relative humidity. Air was cooled and dehumidified using ammonia-refrigerated brine coils. The supply air was then reheated with a steam coil. The amount of air to be reheated was controlled by a duct thermostat-actuated bypass damper. In addition, each of the five wards also had its own thermostat controlled reheat coil.[11]

• In 1906, the banking offices of Kuhn, Loeb & Co. at William & Pine Streets in New York were cooled with a system designed by Arthur Feldman. An air quantity of 390,000 cfm (184 040 L/s) was circulated over galvanized pipe banks through which calcium chloride brine was circulated. A 20-ton (70 kW) capacity ammonia compression refrigerating system was used to cool a tank of brine. The cooling load design was 30 tons (106 kW), and the brine tank was sized so that the refrigeration could be started before normal working hours to provide stored cooling.[12]

• In 1907, a carbon dioxide direct expansion air-cooling system, designed by Andrews & Johnson Company and Fred Wittenmeier of Kroeschell Bros. Ice Machine Company was installed to cool the banquet and meeting rooms of the new annex of the Congress Hotel in Chicago. The system so pleased the hotel management during the summer of 1907 that they planned to double its size of the system so the corridors and "French Room" restaurant could be cooled (see *Figure 3*).[13]

• In 1910, another Wittenmeier-designed comfort cooling installation was installed at the Blackstone Hotel in Chicago. That system used direct expansion carbon dioxide coils placed in air washers to cool the banquet hall, restaurant, grill, café and barbershop.[14]

Willis Carrier Puts It All Together

The first year of the new century also began the career of the one engineer who would combine creativity, science and business sense like no other: Willis Haviland Carrier.

Willis Carrier went to work for Buffalo Forge Co., a leading manufacturer of fan heating apparati, in 1901. He was assigned to research and development, convinced management to start a research lab and within a year was asked to solve a humidity control problem at a printing plant. Carrier investigated potential solutions theoretically and experimentally and decided to control the humidity with cooling coils. The system was designed and installed at the Sackett and Wilhelms Co. in Brooklyn in 1902.

Unfortunately, the dehumidifying system was retrofitted to an existing hot-blast heating system instead of being designed from scratch as a total system. The system failed to maintain the design conditions and was removed shortly after installation. Carrier later said that he "realized that the design was not the final answer for controlling the moisture content of the air, so I began working toward a design that would be the answer."

Carrier was good at visualization upon observation. When conducting the experiments for the printing plant job with refrigerated pipe coils, he realized that an air washer could be used to dehumidify air. Carrier later recalled:

... "We had the apparent paradox of reducing the moisture in the air by bringing it into contact with moisture. Of course the explanation was simple. The temperature of this water was below the dew point or condensation temperature of the entering air. Why should we not, then, spray the cold water into the airstream, thus increasing the surface of contact and reducing the resistance to airflow."

"These early experiments ... started the trend of investigation through which many of the fundamental laws of evaporation, humidity control and of heat transfer were established... ."[15]

The process of thought during the 1902–1903 experiments was revealed sometime later. Commenting upon his experiments with calcium chloride to dehumidify air, Carrier said:

"When calcium chloride, or any other substance, absorbed moisture out of the air, an exactly corresponding amount of latent heat was released in the form of sensible heat. ... the observation of this one phenomenon led to a train of thought, which eventually was to become important. This experiment disclosed the interrelation of latent and sensible heat in the air when its moisture content was altered without the addition or subtraction of external heat. It also led to complementary experiments upon the process of evaporation of water into air and, finally, into the development of the principles upon which air conditioning was founded ... ."

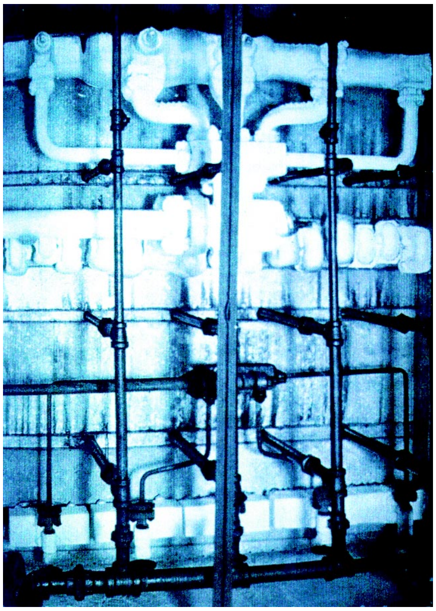

Figure 3: Cooling pipes in the air washer installed at the Chicago Congress Hotel in 1907. From a catalog by Kroeschell Bros. Ice Machine Co., ca. 1912.

Carrier's scientific engineering process "also led to a further study of the need for devising suitable equipment for carrying out air conditioning processes as well as to thought upon the need of various industries for maintaining atmospheric conditions, independently of external weather variations."[16]

Carrier designed a spray-type air conditioner, a very sophisticated air washer, with which he could control the absolute humidity of the air leaving the conditioner, and ultimately, the relative humidity of the conditioned space. On Sept. 16, 1904, Carrier applied for a patent on the device, "Apparatus for Treating Air," receiving U.S. Patent 808,897 on Jan. 2, 1906. The Buffalo Forge Company began manufacture of the air washers in 1905 (see *Figure 4*).

One of Carrier's spray conditioners was sold to the Chronicle Cotton Mill in Belmont, S.C., in 1906. The device did not work as well as Carrier had hoped. Carrier astutely observed the results, took measurements at the plant and studied the data. He later said:

"In this study an interesting fortuitous relationship was discovered between the cooling capacity of saturated air and the relative humidity which could be maintained with varying temperature, that is the differential between the dew point of air introduced and the temperature of the room was practically constant for any relative humidity irrespective of the variation in basic temperature. For a fixed room temperature, of course, this was obvious and was the foundation upon which the basic patent for the dew point method of controlling relative humidity was obtained."[17]

Carrier's device for dew point control received U.S. Patent 854,270 on May 21, 1907. During this time, he began development of his psychrometric chart and formula. Handwritten formulas and charts dated 1908 once existed in the engineering files of the Buffalo Forge Company. His formulas, psychrometric chart and apparatus for controlling air were discussed in two papers presented before The American Society of Mechanical Engineers in 1911.[18]

Some years later, Carrier related his thought process in developing the psychrometric chart:

"All of these early experiences in the laboratory and in practical application brought to our attention fundamental re-

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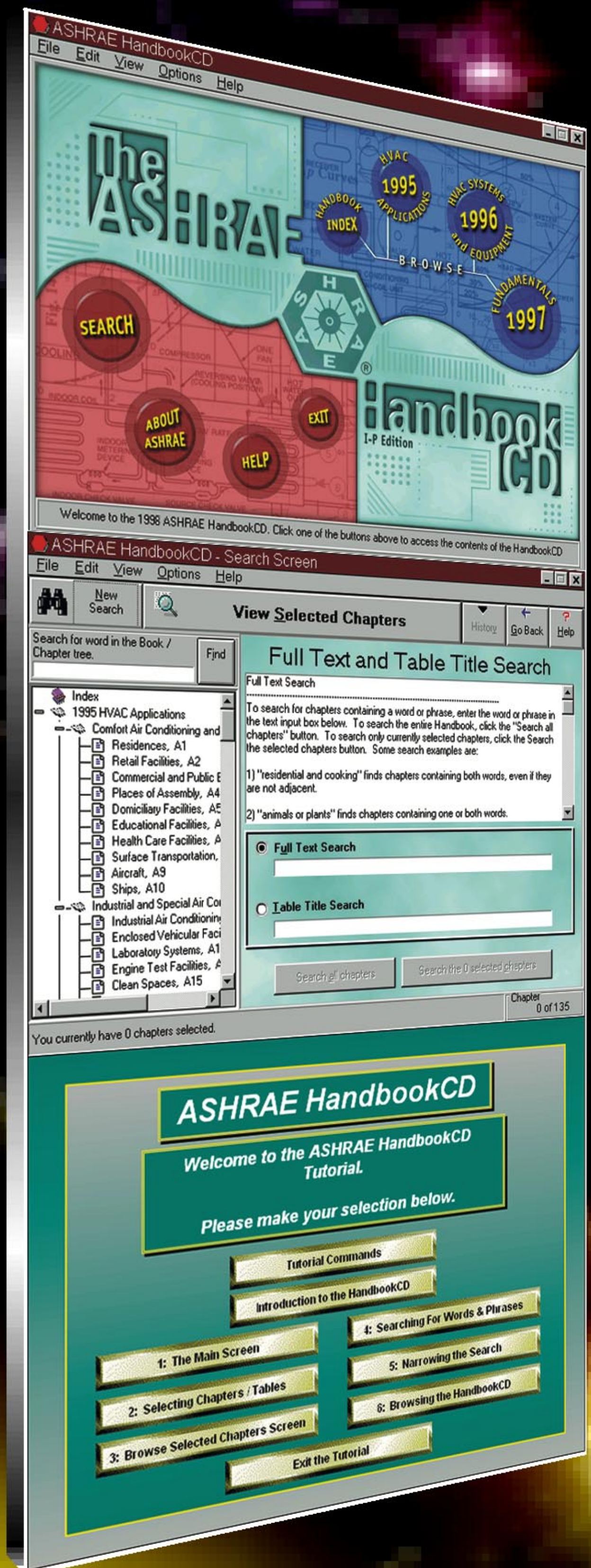

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lationships and natural laws which we investigated and finally succeeded in rationalizing on a mathematical basis. For instance, it was noticed that the saturation temperature of the air, when passed through a chamber in which the spray water was simply recirculated, was exactly the same as the wet-bulb temperature of the entering air.

"This same fact subsequently was observed in tunnels in which wet material was being dried. Under these conditions it was noted that the wet-bulb temperature remained essentially constant throughout the length of the tunnel while the dry-bulb temperature of the air was being reduced, due to absorption of sensible heat by evaporation, and coincidentally the dew point was increasing.

"An analysis of this showed that the total heat of the air remained constant throughout such a saturation process and that the wet-bulb temperature could be taken under any condition as a measure of the total heat of the air. These facts were rationalized and formulated, establishing the basis for the Psychrometric Chart, now in general use."[19]

Air Conditioning—Named, Defined, Corporatized

Stuart Cramer, credited with independently discovering some of the relationships that Carrier had used to arrive at his rational psychrometric formulas, coined the term "air conditioning." Cramer, a textile engineer from Charlotte, N.C., first used the name in a patent filed in April 1906 (U.S. Patent 852,823). He also mentioned it in a paper "Recent Developments in Air Conditioning" read before the convention of the American Cotton Manufacturers Association in May 1906.[20]

G. B. Wilson, in 1908, was the first to define modern year-round air conditioning.

"1. To maintain a suitable degree of humidity in all seasons and in all parts of a building.
2. To free the air from excessive humidity during certain seasons.
3. To supply a constant and adequate supply of ventilation.
4. To efficiently wash and free the air from all micro-organisms, effluvias, dust, soot and other foreign bodies.
5. To efficiently cool the air of the rooms during certain seasons.
6. To either heat the rooms in winter or to help heat them.
7. To combine all the above desiderata in an apparatus that will not be commercially prohibitive in first cost or cost of maintenance."[21]

In the meantime, Carrier had convinced the Buffalo Forge management that humidity control for industry could make money for the company, and that Buffalo Forge should be the first manufacturer to pursue this new field and manufacture equipment for it. The Carrier Air Conditioning Company of America was established as a subsidiary of Buffalo Forge Company in 1907.

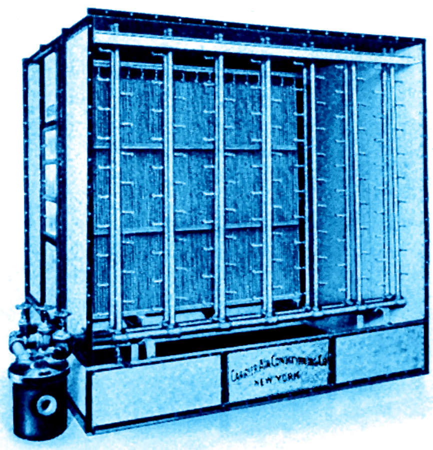

Figure 4: Willis Carrier's "apparatus for treating air." From a catalog by Carrier Air Conditioning Co. of America, 1908.

Now Carrier had a sales force to sell the new product and an engineering staff to design systems. The Buffalo Forge subsidiary was apparently the first manufacturing-engineering combination in the history of air conditioning (see *Figure 5*).

Willis Carrier's Contribution

Carrier had a vision of an entirely new industry, but he did not invent air conditioning nor was he the first to take a scientific approach to it. However, Carrier's work in air conditioning was unlike what anyone had done up to that time.

Hermann Rietschel had postulated the early science of air conditioning, but recognized its limits and suggested experimentation. Alfred Wolff had applied a calculated approach to the design of the year-round air-conditioning system at the New York Stock Exchange, but paused until he was asked as a consulting engineer to design another comfort cooling system. Wolff did not design the equipment itself but used what was available in the marketplace.

Carrier, when given the printing plant job, had been able to define the problem and come up with what he thought was a workable solution. When that solution was not the best answer to the problem, Carrier learned from the failure and from further experiments. From this, he discerned another workable solution—the design of a spray-type air washer to saturate the air.

The device could be used to achieve any desired level of humidity. When that solution did not give the desired result at a cotton mill, Carrier learned from that failure and further observations and experiments to further refine both the theory and the apparatus. The result was dew point control and the psychrometric chart.

Carrier possessed keen powers of observation; an ability to see relationships among various theories, data and results; an ability to learn from each experiment and job design; an abstract thinking ability coupled with a creative mind; and a very good business sense. They were combinations rarely seen in one person.

Carrier's great contribution was in his ability to see that air conditioning could be an industry, and that he took the steps to establish such an industry by combining the scientific method, engineering and business. Although none of Carrier's earliest work in air conditioning involved comfort cooling, his efforts contributed much to later comfort cooling engineering.

Mass Application of Air Conditioning—The Movie Houses

The earliest comfort-cooled motion picture theaters employed direct expansion systems using carbon dioxide refrigerating systems. Such was the type said to have been installed in 1911 at the Orpheum Theater in Los Angeles using refrigerating equipment made by Kroeschell Brothers Ice Machine Company. This system was probably designed by Frederick Wittenmeier who later designed a number of theater air-cooling systems.[22]

These carbon dioxide systems were not marvels of air-conditioning engineering. They did not effectively address the proper distribution of air, nor did they result in good humidity control. They were really just heating systems to which had been added some refrigerating equipment for summer cooling.

For many years, heating and ventilating engineers had argued about the best means to distribute air in the fan-type systems that had become popular for large buildings by the turn of the nineteenth century. Much of the discussion of distribution had settled on the merits of introducing supply air either at the floor or at the ceiling. Each method had its proponents. Air from above would enter the breathing zone first and flush stale air to the floor. But heated air rose. Many engineers felt it was better to supply it at the floor and let it rise to the ceiling.

In the case of a theater it made sense to introduce heated air at the floor so the patrons would be cozy in winter. Most of the early theater systems were designed to optimize heating, and so used upward distribution from floor outlets. Some of them were retrofitted with cooling systems, with poor results. Cold air introduced in proximity to people could result in very uncomfortable conditions. It was not unusual to find theater patrons wrapping their feet in newspapers, or carrying blankets to "refrigerated" theaters in hot weather.

Many of the first successful air-conditioning systems, such as Alfred Wolff's New York Stock Exchange design, recognized the necessity of distributing the supply air from many openings in the ceiling. The cold air diffused and mixed with the room air before striking the occupants, thus arriving at the comfort zone at a reasonable temperature, humidity and velocity.

The first example of a well-engineered theater system seems to have been provided by Carrier Engineering Corporation. This firm designed and installed an air washer-type cooling system in 1922 at the Metropolitan Theater in Los Angeles using carbon dioxide refrigeration equipment manufactured by the Carbondale Machine Company.[23]

Leo Logan Lewis, one of Carrier's partners, designed a downward system specifically engineered for theaters. He also applied a design featured in many fan heating systems, that is, bypassing some of the airstream around the heat exchanger. Lewis bypassed some of the supply air around the air washer, and remixed it before distribution to the theater, resulting in better humidity control.

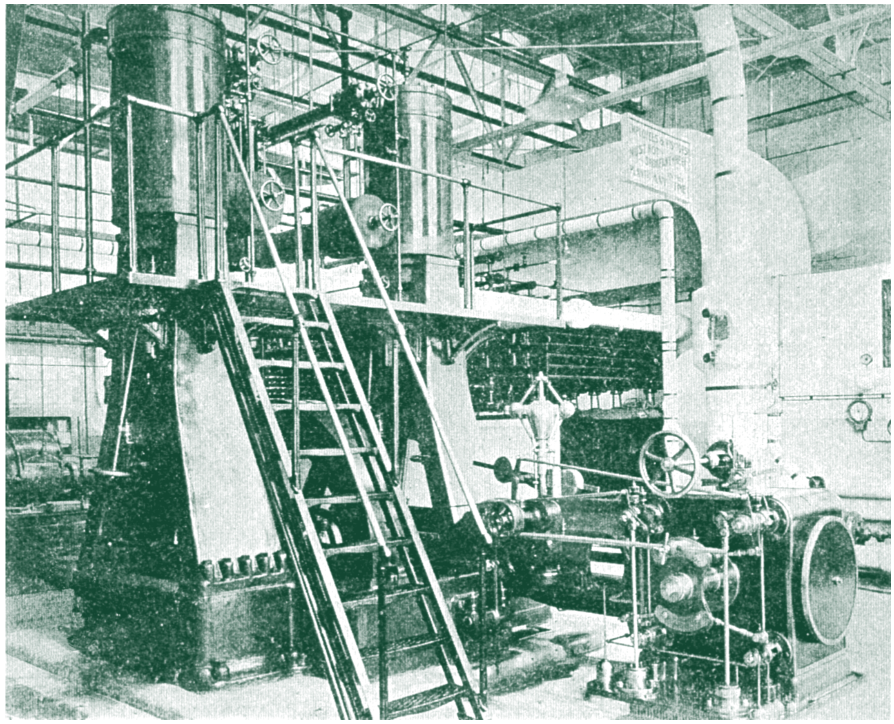

Figure 5: Carrier air-conditioning equipment in 1917. Ammonia compressor driven by steam engine in foreground. The air washer is to the right. From **The Heating and Ventilating Magazine,** *January 1917, p. 19.*

The bypass idea was proposed as early as 1895 by S. H. Woodbridge for an air-cooling system for the U.S. Capitol. Woodbridge suggested "... a part only of the air may be so sharply chilled as to remove the weight of moisture necessary to insure dryness, and this chilled and dried air may then be passed on and mixed with the untreated part, resulting in the drying and cooling of the entire volume of air."[24]

Bypass was actually used for cooling at a theater in Vienna about 1909.[25] Combining the idea of bypass and recirculation was advocated in the early 1900s by Louis Schmidt: "Auditorium cooling would be to a considerable extent on the closed system. To avoid excess of humidity for comfort some of the returning warm air is bypassed and mixed with the cooled air."[26]

Lewis combined all three ideas of downward diffusion, bypass and recirculation in one system with automatic control. Lewis' Metropolitan Theater system proved that theater air conditioning was a workable idea.

These new approaches to air-conditioning engineering were further refined in subsequent theater applications by both Lewis and by his competitor, Walter Fleisher. By the late 1920s a number of engineers were specializing in air conditioning, and numerous engineering articles appeared concerning the air conditioning of theaters and public buildings.

The new engineering methods reduced system and operating costs, making air conditioning much more attractive to those responsible for the explosion of theater construction and renovation which began in the 1920s in the U.S. Whereas only four theaters were cooled in Chicago in 1922, 14 were in operation three years later. It was projected that 50 theaters in New York would be cooled by 1927.[27] As competition among these theaters increased, there was further need to reduce installation and operating costs, creating more impetus for better engineered systems.

Perfection of an engineered approach facilitated the proliferation of air conditioned motion picture houses, further exposing the public to air conditioning. The business world was shown that it made economic sense to install air conditioning not only in public places, but also in offices and even homes. Much progress had been made in reducing the cost and improving the design of large air-conditioning systems. However, these large systems were for the most part unsuitable for small installations.

Still, it seems that a yearning for the comforts of air conditioning had been planted. Although air conditioning was still too expensive for mass application, the next two decades would see such technical advance that comfort cooling would seep its way into daily life. Soon cooling would become a necessity for modern life. Future articles in this ASHRAE series on air-conditioning history will discuss the advances in home air conditioning, in office buildings and in automobiles.

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