A History of the Centrifugal Refrigeration Machine*

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THERE is in operation today throughout the world a total installed capacity of approximately 300,000 tons of centrifugal refrigeration. Although originally developed to chill water for air conditioning service, its application has been extended into almost every field requiring the production of cold—for comfort, for industrial and for commercial processes—for temperatures from +60°F. down to —110°F.—in effect almost every conceivable refrigerating duty.

It is difficult to realize that 30 years ago the centrifugal principle was just a dream, that 20 years ago saw the first practical machine built, and that ten years ago textbooks still dismissed it with a casual reference. Although the past two decades have given rise to an unprecedented expansion in refrigerating development and enterprise, there have probably been few inventions that have been as revolutionary in fundamental concept and as important in their impact upon the trend of the industry, as the introduction of centrifugal refrigeration.

The Economic Need

AN invention is an empty thing unless it fulfills an economic need. The need which gave birth to the centrifugal idea arose between 1905 and 1920 when the men who had pioneered in air conditioning were starting to use refrigeration in order to produce cooling and dehumidification of air. This was before the days of comfort cooling, although there had been a few installations even then. The importance of air conditioning in those days lay in the control of atmosphere for industrial processes.

Finned heat exchangers such as present-day air cooling coils were unknown at that time, and bare pipe coils were impractical on account of cost. Cooling and dehumidifying of air was done almost entirely by the use of spray washers, in which a finely atomized cloud of chilled water provided the contact surface for the absorption of heat from the air being cooled.

The spray washer was a very satisfactory cooling and dehumidifying device, as is evidenced by its continued use today. The equipment which chilled the water, however, was eminently unsatisfactory. About the only machines of commercial importance were ammonia and CO_2 compression, and ammonia absorption. Ammonia was a hazardous refrigerant for air conditioning. Carbon dioxide, while safe, was inefficient and quite expensive. No refrigerant that was both safe and thermodynamically satisfactory had been made available for reciprocating machines. Yet safety was a primary requirement for this type of service, since the safety of hundreds of employees could be endangered by an accident to refrigerating machinery employing a hazardous gas.

Another very important limitation to machines of that day was the difficulty of controlling capacity of a machine which was cooling water. An air conditioning load is a variable load, subject to the vagaries of outside weather and the process load it may be serving. A machine chilling water for such a service must be extremely flexible, and automatically so, for if its capacity does not continually match the changing load, the water will either be too warm or will freeze into ice.

At that time expansion valves and compressor capacity control were manual, which required entirely too much attention by the operator. Shell and tube coolers could not be used because of the hazard of freezing up, even with

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In this interesting account of the development of the centrifugal refrigeration machine, the author reminds us that the first practical machine was built only twenty years ago, and that even ten years ago this invention was not considered seriously. In a final section on applications, he states that although the prevalent idea is that centrifugal refrigeration is used chiefly for comfort cooling, the machine is well suited to the production of very low temperatures.

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From 1941

comparatively high water temperatures. The conventional method of cooling water was by the use of the baudelot cooler, which for air conditioning service was frequently combined with a spray washer with sprays cooling the air in the upper chamber and the warm water falling over direct expansion ammonia coils in the lower section.

The steam jet machine, invented by Maurice LeBlanc in France, and used to a considerable extent on French battleships, appeared to have attractive possibilities. It was not until a little more than a decade ago, however, that it was perfected sufficiently to gain commercial importance, and of course its inherent limitations — the necessity of a cheap source of steam and copious condensing water—were recognized at that time. For a refrigerating machine to fill the economic need in the broadest possible way, it was essential that it could use any of the available important primary sources of energy.

Early Investigations and Inventions

ALTHOUGH the idea of applying centrifugal compression is probably fairly old, the first competent analysis and experimental groundwork was not done until between 1910 and 1915. This pioneering was likewise done by Maurice LeBlanc, who not only made quite a thorough study but built a workable experimental machine and obtained a broad patent on the centrifugal idea.[1]

LeBlanc experimented with two refrigerants — carbon tetrachloride and water vapor. Carbon tetrachloride was not a satisfactory refrigerant because it was unstable and dissociated sufficiently to form decomposition products which ruined the compressor. He was on the proper trail, however, because CCl_4 has thermodynamic properties (including a high molecular weight) which would otherwise have made it a suitable refrigerant for centrifugal compression. LeBlanc's work with water vapor (Fig. 1) did not bear fruit largely because of his inability to design an impeller of sufficient mechanical strength for the high rotative speeds necessary with a refrigerant of such low molecular weight. A secondary reason for his failure to build a practical machine was his lack of a satisfactory shaft seal to keep air out of the system.

There were other inventors at about the same period who discussed the feasibility of the centrifugal principle, and it may be that one or more of them built experimental equipment. It is fairly certain however that none of them made nearly as much progress as LeBlanc, and their contribution to the art is not significant.

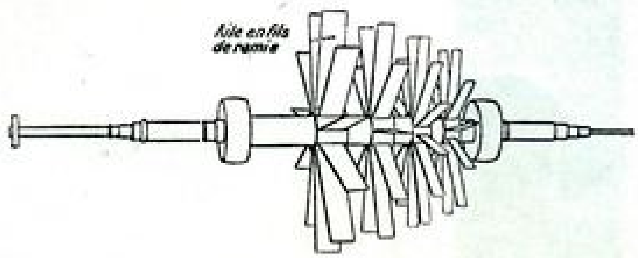

Fig. 1. LeBlanc centrifugal rotor.

The need for a more satisfactory method of cooling water led Willis H. Carrier in 1916 to investigate the thermal and commercial possibilities of various schemes, each of which he subjected to a rigorous theoretical analysis. Among other ideas, Dr. Carrier was impressed by the Taylor hydraulic air compressor, which entrains air at the top of a moving column of water, and compresses it to that pressure existing at the bottom by virtue of the column's static head. The power input is that required to pump the water, and the efficiency is good. The principle is suited to the compression of a vapor for refrigeration, and of course a centrifugal action can be substituted for the column of water.

This principle inspired Carrier to consider the basic refrigeration cycle for a vapor alone from the same point of view. He reasoned that compression could be produced by a gravitational column (Fig. 2) such as might exist if the evaporator were located at the top of a mountain and the condenser in the valley beneath. If sufficient height is provided in the column, the pressure in the condenser will be enough just from the column's own weight to permit condensation at the available temperature. The gas will continue to evaporate from the evaporator, flow to the condenser, and be condensed there, and all the work required for theoretical compression is provided by the external force of gravitation. This is not perpetual motion, for it is evident that the condensate must be pumped from the condenser back to the evaporator in order that refrigeration can continue, and that just as much work is required in pumping the liquid as is required in the gravitational compression of the gas.[3]

The illustration shows a centrifugal pump for elevating the liquid. It is obvious that instead of the gravitation column, a centrifugal compressor (or *gas pump*) can be substituted, thus dispensing with the liquid pump. Since the gas head and liquid head are the same, the centrifugal compressor would operate at the same peripheral speed as the centrifugal pump.

It is also evident that the higher the molecular weight of the refrigerant gas which is used in the column, the lower the pumping head,

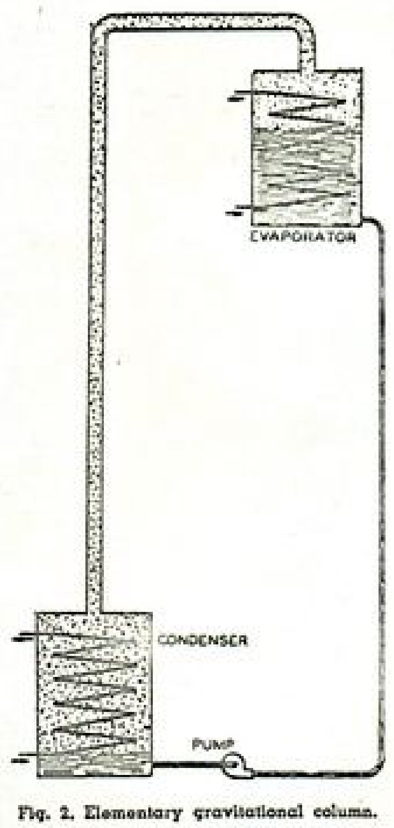

Fig. 2. Elementary gravitational column.

[1] Memoires de la Société des Ingénieurs Civils, Feb. 1913.

[3] "Centrifugal Compression as Applied to Refrigerants," W. H. Carrier, *Refrig. Eng.*, Feb. 1926.

Table 1. Requirements of a Practical Refrigerant for Centrifugal Compression

Requirement	*Dielene* $C_2H_2Cl_2$ (Dichloroethylene)	*Carrene* #1 CH_2Cl_2 (Methylene Chloride)	*Carrene* #2 $CFCl_3$ ("Freon-11")
Thermodynamic			
High Molecular Weight	97.0	84.9	137.4
Suitably Large Volume per Ton*	41.2	27.7	15.8
Boiling Point near 100 F.	98.6°/131°	105.2°	74.7°
Low Pressure Difference (Lb./Sq.In.)*	7.12	9.92	16.56
High Cycle Efficiency**	89.8%	89.6%	90.9%
Low Value of $\frac{C_p}{C_v} = k$	1.14	1.18	1.125
Stable—No Dissociation	Yes	Yes	Yes
Physical and Physiological			
Non-Toxic	Yes	Yes	Yes
Non-Corrosive	Yes	Yes	Yes
Non-Inflammable	Relatively	Yes	Yes
Odorless	Yes	Yes	Yes

* At 40° F. Evaporation and 100 F. Condensing.
** Without Liquid Intercooling.

and the lower the peripheral speed of the equivalent centrifugal compressor. Likewise, for the same total work with a shorter gravitational column, more liquid would be pumped, implying that a dense refrigerant with a high molecular weight would have a low latent heat. Obviously, a heavy gas is desirable for centrifugal compression in order to reduce the number of impeller stages and the peripheral speed of each.

The foregoing analysis indicated to Dr. Carrier that for centrifugal compression to be a success, he would have to find a refrigerant of suitable thermodynamic, physical and physiological properties.[3]

Refrigerants for Centrifugal Compression

TABLE 1 shows the requirements of a practical refrigerant for centrifugal compression. Note the high molecular weights of these refrigerants compared with ammonia (17) and water vapor (18), and the difference in volume per ton (ammonia 1.7 and water 482.)

None of these substances was in use as a refrigerant; the Freons had not been developed; neither dielene nor methylene chloride was available in this country. Ethyl chloride was considered, but its volume was too small, its boiling point and molecular weight both too low; furthermore it is quite inflammable. Dielene seemed to have most of the requisite properties, if obtainable. When Dr. Carrier went to Europe in 1921 he found that one of the divisions of the chemical trust in Germany was manufacturing dielene on a small scale for use as a cleaning fluid, and he was able to arrange for its importation. It was not until some time later during actual use of this chemical as a refrigerant that it was discovered to be composed of two isomers with different boiling points. It was finally necessary to have it purified by distillation to an average boiling point within the range 122 to 125° F., in order to stabilize the performance of the machines and predict their capacity.

Dielene was used successfully for about four years. By this time the machines were an outstanding commercial success, and when methylene chloride was found to have suitable properties, the anticipated demand was sufficient for R. & H. Chemicals Company to build a plant for its production in this country. Carrene, as it was named, could be used in the dielene machines with minor modifications, was entirely non-inflammable, had a single boiling point, and gave somewhat greater tonnage capacity for the same size of machine.

It is interesting to review the entire list of refrigerants which have been used at one time or another for centrifugal compression (see Table 2). Inspection of this tabulation shows many gases quite far from the ideal with respect to thermodynamic and physical properties. Water vapor, for instance, has such a low molecular weight and high boiling point that the peripheral speed of the impellers must be extremely high; yet its availability at no cost and its safety made it a preferred choice by Le-Blanc in his experimental machine, and by the Ingersoll-Rand Company when the latter developed their commercially successful machine about 1935. Ammonia was also used in two installations abroad by Brown-Boveri; obviously the small volume per ton made it feasible only for very large capacities.

In 1931, the Frigidaire Division of General Motors, in collaboration with du Pont, developed the family of Freon refrigerants, and introduced Freon-12 for general reciprocating machine duty. Dr. Carrier foresaw the possibilities of this refrigerant group early in 1931, with a result that Freon-11 was introduced in 1933 for centrifugal machines, after a complete redesign of the compression and purge systems for this gas. Its high molecular weight combined with its other desirable thermodynamic and physical properties, has made it the standard refrigerant for centrifugals today.

While on the subject of refrig-

Table 2. Refrigerants Used in Centrifugal Machines

Refrigerant	*Formula*	*Molecular Weight*	*Boiling Point, F.*	*Date*	*Manufacturer*	*Remarks*
Carbon Tetrachloride	CCl_4	153.8	170.0	Abt. 1912	Le Blanc	Experimental
Water Vapor	H_2O	18.0	212.0	Abt. 1912	Le Blanc	Experimental
Dielene (Dichloroethylene)	$C_2H_2Cl_2$	97.0	98.6/131	1922	Carrier	First Practical Machine
Trielene (Trichloroethylene)	C_2HCl_3	131.4	189.0	1925	Carrier	Only One Built
Ammonia	NH_3	17.0	—28.0	1925	Brown-Boveri	
Carrene #1 (Methylene Chloride)	CH_2Cl_2	84.9	105.2	1926 1933	Carrier Brown-Boveri	
Ethyl Bromide	C_2H_5Br	109.0	102.0	1932	Brown-Boveri	
Ethyl Chloride	C_2H_5Cl	64.5	54.0	1935	Brown-Boveri	
Water Vapor	H_2O	18.0	212.0	1935	Ingersoll Rand	
Carrene #2 ("Freon-11")	$CFCl_3$	137.4	74.7	1933 1939 1939	Carrier York Worthington	
"Freon-12"	CF_2Cl_2	120.9	—21.7	1934	Carrier	For Low Temp. Duty
"Freon-113"	$C_2Cl_3F_3$	187.4	117.6	1938	Trane	

[3] "Comparison of Thermodynamic Characteristics of Various Refrigerating Fluids," W. H. Carrier and R. W. Waterfill, *Reg. Eng.*, June, 1924.

ants, it is appropriate to mention their performance with respect to the standard of comparison, the Carnot cycle. It was noted (Fig. 3) that dielene, methylene chloride and Freon-11 have approximately equal cycle efficiencies at 40°F. evaporator and 100°F. condenser. In a similar comparison of Freon-11 with ammonia and Freon-12, it will be noted that not only is Freon-11 substantially more efficient than the other two, but that by the use of an economizer to permit liquid intercooling, this cycle efficiency is vastly improved. This means that with compressors of equal mechanical efficiency, a centrifugal using Freon-11 with intercooling will have a substantially lower horsepower per ton than the reciprocating machine where intercooling is not feasible except for staged machines.

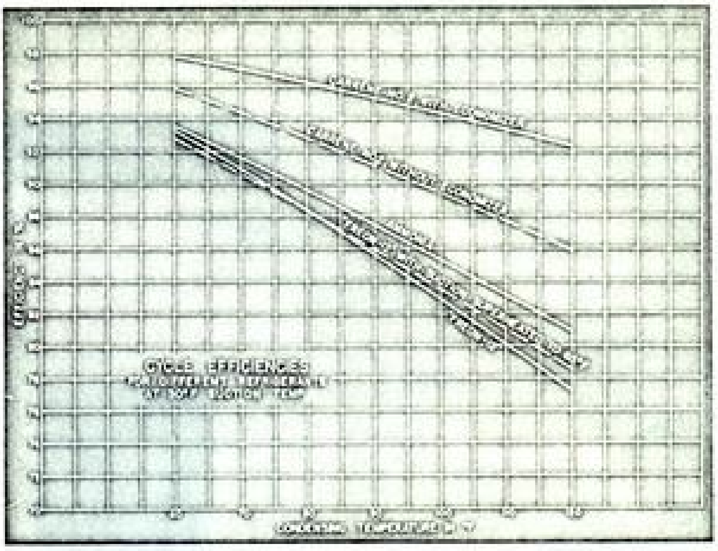

Fig. 3. Cycle efficiencies of refrigerants at 30° F.

Design Problems of the First Machine

CHOICE of a suitable refrigerant opened the door to the centrifugal principle, but left many important design problems to be solved. Chief among these was the choice of a suitable compressor. Centrifugal air compressors were in common use, but handling a vapor like dielene was considerably different from air. There were thermal and hydraulic considerations involving complete redesign of impellers and diffusers. There was the sealing problem, for these machines were to operate under vacuum, and a practical, fool-proof, and long-lived shaft seal was essential which would remain tight not only during operation but during shut-down as well. Finally, a lubricating system had to be devised to operate with a refrigerant which was miscible with oil in all proportions, and which was absorbed into the oil from the gaseous phase whenever the two were in contact.

Dr. Carrier was unable to arrange for the adaptation of a centrifugal air compressor in this country at a reasonable price—at that time they cost as much as an entire refrigerating plant. After considerable search abroad, he located four sources of supply in Switzerland and Germany and ultimately made arrangements with the Jaeger Company of Stuttgart for their manufacture. This firm designed a very satisfactory compressor to Carrier's specifications, but the first seal didn't work at all, and he had to rebuild it completely after it arrived in New Jersey.

Another design problem related to the evaporator. The conventional double pipe cooler was out of the question due to the large volumes of vapor to be removed; the flooded shell and tube evaporator was not feasible for a refrigerant like dielene where the submergence of liquid raises the boiling point excessively at the bottom of the shell. This difficulty was solved by the use of a flash evaporator wherein the refrigerant was poured onto a distributing deck and rained over the tubes below (Fig. 4).

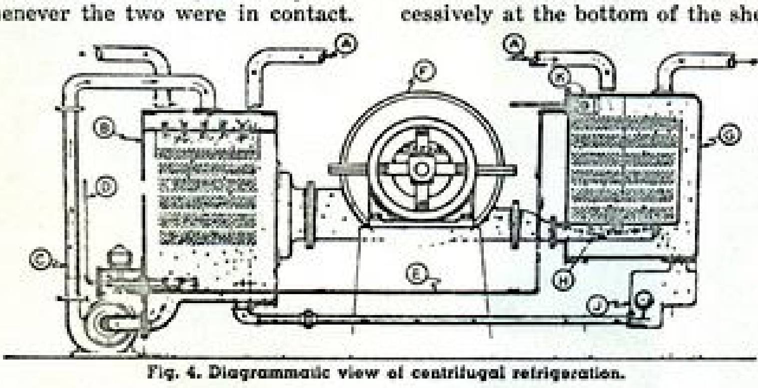

Fig. 4. Diagrammatic view of centrifugal refrigeration.

A—Water
B—Evaporator
C—Evacuator
D—Air vent
E—Evacuator pipe
F—Compressor
G—Condenser
H—Saturator
J—Trap
K—Auxiliary condenser

Practical Centrifugal Machines

CARRIER'S machine was the first practical centrifugal refrigerating machine. It had a four-stage compressor using dielene for the refrigerant, and had a capacity of about 70 tons of refrigeration for air conditioning service. The first public demonstration was given in 1922 before the A.S.R.E. at the Carrier Engineering Corporation's offices in Newark, N. J. to an interested but somewhat skeptical gathering of men prominent in the industry. Two years later this same machine was sold to the Onondaga Pottery Company of Syracuse, N. Y., where it has operated continuously ever since.

As is the case with every development, later machines incorporated refinements in design and arrangement. Cast iron coolers and condensers were used with straight-through tubes that could be easily cleaned. Compressors with dielene, and subsequently methylene chloride, were five- and six-stage, which in many cases permitted direct connection to 3600 r.p.m. motors. Refinements were made in the liquor pump, seal and evacuator-purging system. The appearance was gradually streamlined.

A single-stage compressor was developed in 1930 for small tonnages, but found rather limited application. The chief drawback to

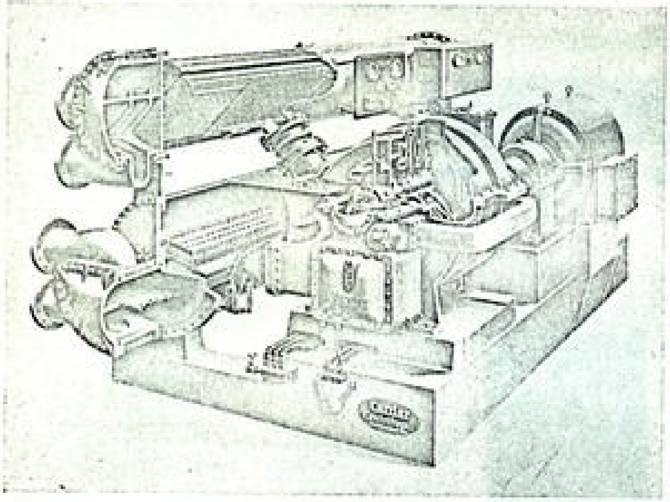

Fig. 5. Cutaway of Type 17-M machine.

any single-stage machine, irrespective of the refrigerant employed, is the inability to obtain more than about 60°F. temperature difference between evaporator and condenser without entering a range of gas velocities above the critical velocity. This prevents good efficiency from being realized.

The development of Freon-11 in 1933 made possible a reduction in the number of impellers in multistage machines from five or six down to two, three or four, depending on the desired temperature difference. In other respects the design of the machines remained substantially the same.

In about 1935 Ingersoll-Rand introduced the water-vapor centrifugal machine. The major points of difference between this machine and those using hydrocarbon refrigerants lie in compressor and evaporator. The former requires much higher tip speeds, which means more stages and specially designed, light-weight impellers to produce the head required for water as a refrigerant. A flash type evaporator is used, cooling the water directly as it returns from cooling coils or spray dehumidifier; this eliminates the need for tubes to provide heat interchange.

The Trane centrifugal is an interesting development with the basic objective of building a machine with a capacity from 35 to 100 tons. Two two-stage compressors, each with its own direct driving motor, are piped in series, making a total of four stages of compression. The gas Freon-113, with molecular weight of 187.4 and boiling point of 117.6°F., is well suited to a small machine since it provides gas volumes sufficiently large to make an efficient design possible. This is in effect a hermetically sealed machine, which of course limits the drive to motors of certain current characteristics. Plate fin cooler and condenser are used. A modification of this design is used for larger machines.

The York and Worthington machines are basically similar to the Carrier centrifugal, with the exception of the seal. These machines, first introduced in 1939, use Freon-11.

The Modern Centrifugal Machine

IN 1936 Carrier commenced a very comprehensive basic study to redesign the centrifugal machine for improved efficiency and lower cost without sacrifice of quality. This development, which lasted two years, was very productive of results, as is indicated by the 1938 model (Fig. 5). The major improvements were: important increase in compressor efficiency; development and introduction of Lo-Fin tubing for the cooler and condenser; elimination of the liquor pump by design of the first feasible flooded cooler for centrifugals; standardization of the built-in economizer; and improvement in the evacuating and purging equipment.

With compressors having only two or three impellers, it was possible to design each wheel separate-

(Continued on page 120)

Table 3. Improvement in Heat Transfer of Coolers and Condensers Due to Use of Lo-Fin Tubing

Item	*Cooler*		*Condenser*	
	Plain Tube	*Finned Tube*	*Plain Tube*	*Finned Tube*
Surface Ratio—Outside/Inside	1.185	3.54	1.185	3.54
Water Velocity—Ft./Sec.	6	8	6	8
U_R—Refrig. Coeff./Sq.Ft. Outside Surface	225	335	285	540
U_O—Overall Coeff./Sq.Ft. Inside Surface	201	538	266	840

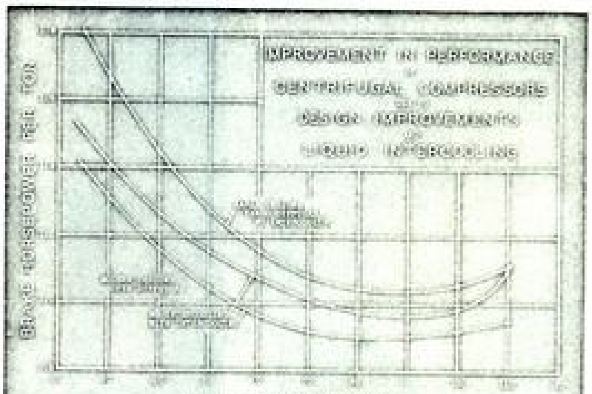

Fig. 6. Compressor performance comparison.

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