Technical Sciences
Academy of Romania
www.jesi.astr.ro

Journal of Engineering Sciences and Innovation
Volume. 1, Issue 1 / 2016, pp. 17-33
http://doi.org/10.56958/jesi.2016.1.1.17

A. Mechanics, Mechanical and Industrial Engineering, Mechatronics

Received ***10 February 2016*** *Accepted* ***12 August 2016***
Received in revised from ***16 June 2016***

Romanian research on refrigeration and air-conditioning

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Abstract. This paper presents results of research developed on refrigeration and air-conditioning systems by a group of professor from the Technical University of Civil Engineering in Bucharest. Theoretical and experimental investigations foccused on renewable energy sources were conducted within national research projects and allowed construction of stands and even modern research laboratories used for student activities as well as an experimental basis for bachelor, master and doctorate works. Research activity also concluded in building industrial pilot systems and papers published in technical journals and magazines, presented in national and international conferences and congresses and Ph.D thesis preparation.

Keywords: renewable energy sources, air conditioning, industrial refrigeration.

1. Introduction

Research developed on refrigeration and air-conditioning systems by a group of professor from the Technical University of Civil Engineering in Bucharest foccussed on the following topics:

➢ **Solar energy**, as one of the most important renewable energy source, represents one of the current solutions to reduce fossil fuel consumption. It is well-known that, worldwide, energy consumption to operate comfort air-conditioning systems represents an important share in the overall energy consumption and this is

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why systems using renewable sources of energy attract growing interest from specialists.

In Romania, comfort air conditioning of low volumes, such as offices, holiday homes, individual residential suites or luxury apartments, is mostly required so air conditioning cooling capacity ranges from 5 kW to 50-60 kW. Cooling power is about 15-20 W/m^3, in areas corresponding to a microclimate for human comfort.

Mostly mechanical vapor compression machines are present on the Romanian market but lately absorption machines have made their way, considering the possibility of using renewable and recoverable energy to power them.

Ammonia is the most frequently used refrigerant for industrial applications (food preservation mainly), but also for air conditioning. In order to support this idea it is worthwhile mentioning that the most important large buildings in Bucharest, used for social and cultural events use ammonia systems, in which only compressors have been imported, the rest of the equipment being produced in Romania.

After the sixties of the last century very large capacity (2-20MW) absorption ammonia-water systems have been designed and produced, especially for the chemical industry. Some of these systems are still in operation provided the company still works.

In the current context, refrigeration systems for comfort air conditioning have to simultaneously ensure environmental requirements, energy saving and compaction of component equipment.

Air conditioned buildings share shows, in Romania, an upward trend which requires from specialists sustained effort to study, research and build equipment that is adapted to the specific needs of consumers.

In this context, in full compliance with global concerns, specialists have designed and developed in the Laboratory of Thermodynamics Department of the Technical University of Civil Engineering Bucharest, experimental stands dedicated to different refrigeration systems for air conditioning.

- Binary ice (ice-slurry) is a mixture of subcooled ice (at -1…-20C) and water, in which the mass ice-fraction may reach 20%-30%. This solution may be used in comfort air-conditioning systems, or in technological systems, to cool the air, by ice-slurry circulation inside the fan-coils. Unlike systems working with cooled water, at 70/120C that are able to extract only sensible heat from the air, the ice-slurry systems mainly extract the latent heat, thus increasing significantly the cooling capacity of this system. As a consequence, the principal advantage is represented by savings in investment and operation costs (pumping energy). Speaking of pumping energy, it is important to mention that ice-slurry circulation leads to greater pressure loss than water, if the mass ice-fraction exceeds a certain limit.

Binary ice systems have been and still are the subject of theoretical and experimental research, done all around the world, since there have not yet been concluded calculation and design solutions for specific applications.

- **Ecological aspects**

The Montreal Protocol, as well as that of Kyoto has introduced a series of limitations on the use of refrigerants which aim at eliminating those products with an impact on the surrounding environment. As a result, R22 must be forbidden by the 1st of January 2015 the latest, even as a product recovered for service activities in the UE countries (The European Law 2037/2000) and the production will be finalized by 2026. The European Union has adopted Regulation CE 2037/2000 regarding substances which diminish the ozone layer (ODS), which regulate the fabrication and use of these substances. Choosing a substitute refrigerant implies respecting the requirements regarding the environment legislation, namely a GWP (Global Warming Potential) and a TEWI (Total Equivalent Warming Impact) as low as possible. A second requirement is related to the refrigerating agent's thermodynamic characteristics such as: pressure – temperature correlation, temperature – specific volume, compression ratio, performance coefficient, thermal conductibility coefficient, dynamic viscosity, latent heat, compatibility with lubricant substances (oil) att. Potential R22 substitutes are: R404A; R407C; R410A; R417 – for installations in the industrial refrigeration and air conditioning. Agents type R507, R424A, R428 and R422A are starting to have a higher efficiency from temperatures over 5 °C; R404A; R407C; R410A; R417; R422 A; R424 A; R428; R507 – for heating pumps.

- One of the main concerns of the **microelectronics industry** is the increased power density reached by the individual components, leading to failure or faulty operation. It is widely recognized that the current cooling techniques using fans, baffles, heat sinks, heat spreaders, will cease to satisfy the projected thermal requirements of the power systems. Several alternative active cooling methods incorporating liquid cooling, Thermoelectric Coolers (TEC's) or phase change techniques, have been extensively explored before, yet the application of classic refrigeration has not been considered to any extent, due to the large size constraints.

Classic studies over the past several decades have acknowledged that vapor-compression refrigerators have been the leading refrigeration technology at the macro scale. The performance of *mini scale* vapor compression refrigerators, however, has not yet been experimentally demonstrated, although recent theoretical studies have presented an overview of refrigeration alternatives for microelectronics cooling, and indicated that at temperatures near room temperature and above, a vapor compression refrigerator may compete successfully with a high efficiency thermoelectric cooler.

A miniaturized refrigeration system, designed to fit the existing microelectronics, with efficient cooling and minimal associated costs has been studied in the Laboratory of Thermodynamics Department of the Technical University of Civil Engineering Bucharest. The main advantage of the proposed method is the sub-ambient cooling of the junction, leading to increased operating speeds of the processors (maintained thus at fairly constant temperatures), also the increased reliability and component feasibility.

2. AIR Conditioning Systems Driven By Renewable Energy Sources - SOLAR COOLING

2.1. Systems using ammonia as a refrigerant

➢ Research activity focused on developing refrigeration systems using renewable energy started in Romania several decades ago. Professors and researchers from the Civil Engineering University of Bucharest and from the Polytechnic University of Bucharest (CHIRIAC et al., 1983) have accomplished a solar driven ice manufacturing system with a capacity of 20000 kg of ice/day. Figure 1 shows this refrigeration system using solar parabolic collectors. Such facilities, solar driven, have been designed and produced under the same supervising authority of the Thermodynamics Department, Civil Engineering University of Bucharest, and they operated until 1990, when re-industrialization of Romania began.

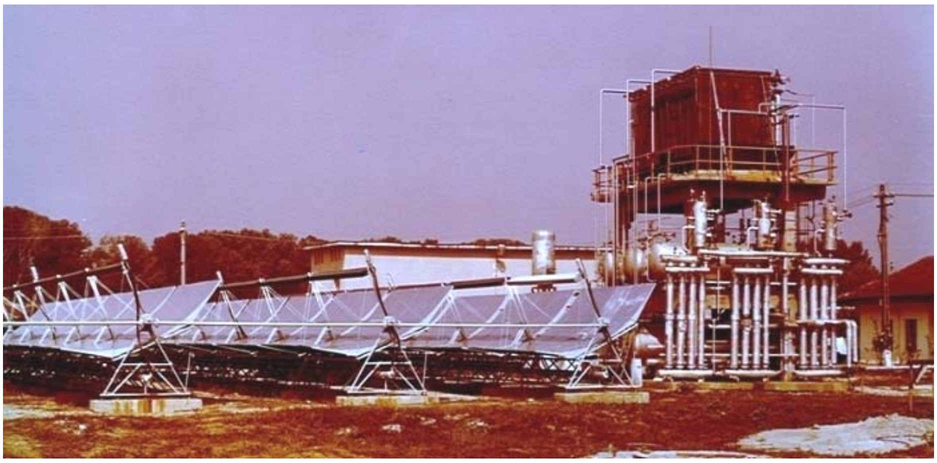
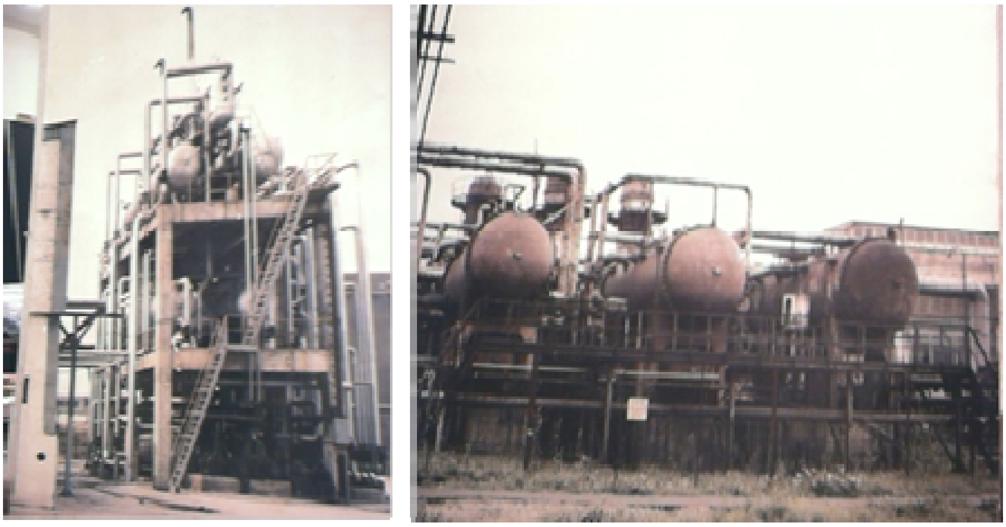


Fig. 1. Ammonia-water absorption refrigeration system driven by solar energy, for cold water and ice preparation, Jurilovca-Tulcea, 1983, designed by Professor Florea CHIRIAC .

➢ Based on the above mentioned research, high capacity absorption ammonia-water heat pumps have been designed and realized (Kim and Infante Ferreira, 2005), namely:

- Resorption system of 2000 kW driven by conventional fuel and waste warm-water of 20 to 30^{o}C that produced warm water of 60-65^{o}C;
- Hybrid compression-absorption heat pump system, electrically powered, with a heating capacity of 7000 kW, recovering heat from warm water of 20 to 30^{o}C, and producing warm water of 60 to 70^{o}C;
- Resorption heat transformer driven by geothermal water of 35-40^{o}C, producing 55-60^{o}C warm water, Figure 2.



a) b)

Fig. 2. a) Resorption heat pump, using ammonia-water solution
b) Hybrid heat pump with mechanical compression and ammonia-water solution, designed by Professor Florea CHIRIAC.

After 1990 research in the field of absorption refrigeration systems and heat pumps, working both with ammonia-water and Li Br-water solution, solar or conventionally driven was in progress in the Thermodynamics Department of the Civil Engineering University of Bucharest., Research activity in Romania is currently focused on improvement of low power absorption systems, using renewable and recoverable energy, for air conditioning purposes.

- Absorption refrigeration system using ammonia-water solution and mini channel heat exchangers, driven by solar energy

The prototype built in the Laboratory of Thermodynamics Department develops a refrigeration capacity of 5-10 kW, depending on the operating conditions. The system was designed for air conditioning in the Teaching Laboratory of the Faculty of Building Services from the Technical University of Civil Engineering. The refrigeration system shown in Figure 3 has several features that place it into the category of the art research, taking into account that: it uses compact mini-channel type heat exchangers with high thermal performance, uses ammonia as a refrigerant in very small quantities, due to the compactness of the system, thus not putting into danger the safety of people, it has a high reliability, it has no moving parts except for the solution pump, it uses solar energy and only in the absence of it, electrical energy. The system's COP is 0.5-0.6. Figure 4 shows the arrangement of solar panels which prepare the necessary hot water to drive the system.

The research team that designed and built this system is part of the Department of Thermodynamics and Thermal Equipment from the Technical University of Civil Engineering Bucharest, and consists of: Anica Ilie (professor), Rodica Dumitrescu (associate professor), Valentin Cublesan (lecturer), Madalina Nichita (lecturer), Razvan Calota (assistant professor), Florea Chiriac (professor), Liviu Drughean (professor), Alexanndru Serban (professor at Transilvania University in Brasov).

Fig. 3. General view of the absorption system

Fig. 4. Arrangement of solar panels

- Compacted version of the system described above was built at SC CRIOMEC SA and is presented in Figure 5.

Fig. 5. Compact absorption refrigerating systems using ammonia-water solution

Figure 5 illustrates the experimental system designed to produce chilled water of 7/12^{o}C for air conditioning. The vapor generator, the condenser, the evaporator and the economizers are mini channel type heat exchangers, made of aluminum. The absorber is an original construction, of mini channel type, with an upper distributor for the poor solution, a lower collector for the strong solution and a median distributor for ammonia vapor injection. The condenser and the absorber are air cooled. The hydraulic diameter of the channels is 1.5 mm. The cooling capacity of the system is 7-10 kW. Hot water prepared by solar energy, with temperatures between 85-90°C was used at the generator for boiling the ammonia-water solution. It is worthwhile mentioning that operation was not possible for water temperatures below 85°C.

- ROBUR type Absorption refrigerating system with ammonia-water solution and modified vapor generator

In the original version of the ROBUR type absorption refrigerating system the vapor generator is powered by gas, while in the modified version, it is powered by solar prepared hot water. Figure 6 shows the plate-type heat exchanger that acts as vapor generator of 25 kW heating capacity.

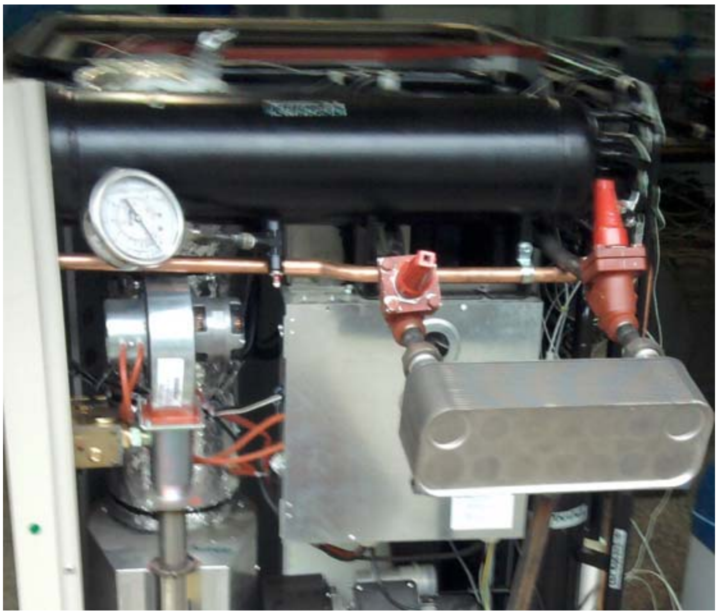


Fig. 6. ROBUR type absorption refrigerating systems using ammonia-water solution and modified vapor generator

Experimental investigation concluded that hot water of 83.4 °C/ 74.6 °C at the inlet / outlet of the vapor generator holds enough thermal energy in order to drive this ammonia-water absorption system; the COP of the system was found to be 0.5.

2.1.Systems using lithium bromide-water solution as a refrigerant

Following the current trend of using renewable sources of energy, specialists of the Department of Thermodynamics and Thermal Equipment from the Technical University for Civil Engineering in Bucharest have designed and built an experimental stand, using a YAZAKY type of absorption refrigerating systems with lithium bromide-water solution. The stand is equipped with measuring devices used to monitor and control the parameters of the working fluids; it is presented in Figure 7.

Fig. 7. YAZAKY type absorption refrigerating system with lithium bromide-water solution

Fig. 8. Array of the flat-plate solar collectors on the laboratory roof

For this experimental stand solar energy has been used as a driving energy source (see Figure 8) for an absorption refrigeration chiller designed to deliver cooled water to an air-conditioning system. For the periods of time when the solar energy does not completely cover the refrigeration demand, a complementary energy source, of conventional type, becomes active (gas boiler). The system was theoretically investigated in order to determine the minimum heat source temperature for which the absorption system still operates, meaning the concentration difference between the strong and the weak solution reaches at least 5%.

The further experimental study aimed to firstly validate theoretical predictions of the minimum heat source temperature and secondly to determine the refrigeration capacity and COP of the absorption chiller, under different operating conditions, namely different heat source temperatures and cooling fluid temperatures.

Experimental investigations carried out showed that solar energy and flat-plate collectors may be used in order to prepare hot water of more than 70°C, even under Romania's specific climate conditions of rather moderate solar radiation. However solar energy may cover up to 74% of the energy demand for air-conditioning over the summer season (June to August). This is why a hybrid system consisting of solar collectors and a conventional gas boiler has been designed and operated.

This experimental study showed that the hybrid solar system, including solar hot water storage, works at desired parameters and represents a viable alternative solution to the conventionally powered air-conditioning systems, both in terms of the refrigerant and the driving source that were used.

The cooling capacity has been found to decrease from 100% to an average value of 74% and the COP has also been found to decrease from 0,64 to 0,517, under cooling medium temperatures ranging from 27 to 35°C and heat medium inlet temperature within (80 …97)°C.

3. AIR Conditioning Systems using Ice Slurry as a cooling medium

Ice-slurry is a viable alternative to the classical air conditioning solution, based on chiller prepared cooled water, taking into account its well known advantages. The main and indisputable advantage of ice-slurry is its high value of ice melting latent heat (4 to 6 times greater) as compared to the sensible heat transferred from humid air to water, as in currently used air conditioning systems. As a positive consequence, ice-slurry systems require lower flow rates of cooling medium to achieve the same cooling capacity and thus lower operating costs.

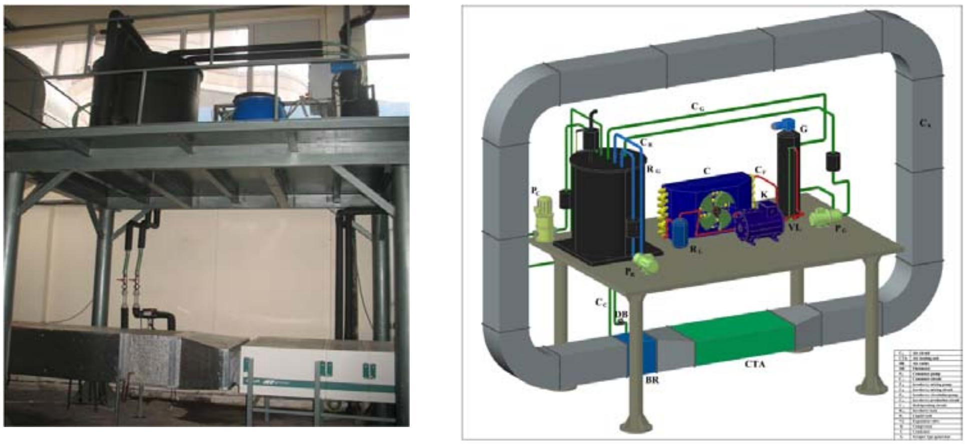
Specialists of the Department of Thermodynamics and Thermal Equipment from the Technical University for Civil Engineering in Bucharest have designed and built an experimental stand able to generate ice-slurry and further use it for comfort air conditioning (Figure 9). The cooling capacity of the system ranges from 3 to 7.5 kW. Ice-slurry is generated in a scraper-type generator (Figure 10 and 11) that is part of a single stage compression system working with R404A, as primary refrigerant. A mixture of ice-slurry, water, and talin (10% mass concentration) represents the secondary cooling medium. A classical type of heat exchanger was used, namely a fan coil, made of copper, with the inner diameter of 9.0 mm, and aluminum fins, of 0.1 mm thickness. Experimental studies have been conducted in order to comparatively analyze the operation of the system working with ice-slurry vs. cooled water, as classical secondary cooling medium. The comparative study has been developed with regard to: overall heat transfer surface; working fluid mass flow rate; thermal performances. Experimental investigations concluded that ice-slurry represents a better option from both energetic and indoor air comfort points of view.

Experimental investigations performed concluded the following: regarding the cooling medium flow rate: the cooling effect provided by 10 to 20% ice mass fraction slurry may be matched by an increase of approx. 30 to 67% in the cooled water flow rate.

Regarding the heat transfer cooling surface area: the heat transfer surface area needs to be enhanced by 25 to 35% if water is to be used as cooling medium as compared to the area required by 10 to 20% ice fraction slurry as a cooling medium.

Regarding indoor air comfort conditions: as the cooling capacity of ice-slurry is higher, for the same air temperature drop, the outlet relative humidity of the air has lower values, which makes ice-slurry a better option regarding the indoor comfort.

As an overall conclusion, in spite of the higher energy consumption of the ice-slurry refrigerating system, it is the authors opinion that ice-slurry may be considered a valid option to cooled water in air-conditioning, based on its advantages, with respect to decreased required surface area, decreased tubes diameters, decreased flow rate and improved indoor comfort.



a). Overall view b) Schematic diagram

Fig. 9. Experimental stand

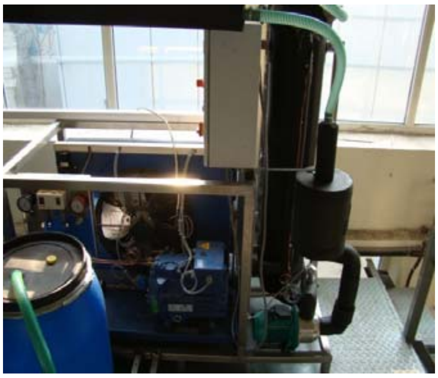


Fig. 10. Ice-slurry scraper-type generator

Fig. 11. Ice-slurry storage tank

4. Mechanical vapor compression refrigeration systems

4.1.Systems using ammonia as a refrigerant

The experimental single stage mechanical vapor compression refrigeration system is shown in Figures 12 and 13. The system comprises the following main pieces of equipment: screw compressor of 60 kW refrigerating capacity (at -10°C evaporation temperature and +25°C condensing temperature); oil separator; plate type condenser; liquid ammonia subcooler; refrigerant receiver of 300 mm diameter and 1500 mm length; ammonia pump; plate type evaporator of 6.2 m² heat transfer area; liquid separator of 300 mm diameter and 2000 mm length;

variable speed centrifugal pumps. The evaporator may be either forced, or gravitationally fed.

This compression system module allows experimental investigations on heat & mass transfer processes in compact mini channel heat exchangers, for comfort and technological air-conditioning consumers. This module may also be operated as a heat pump.

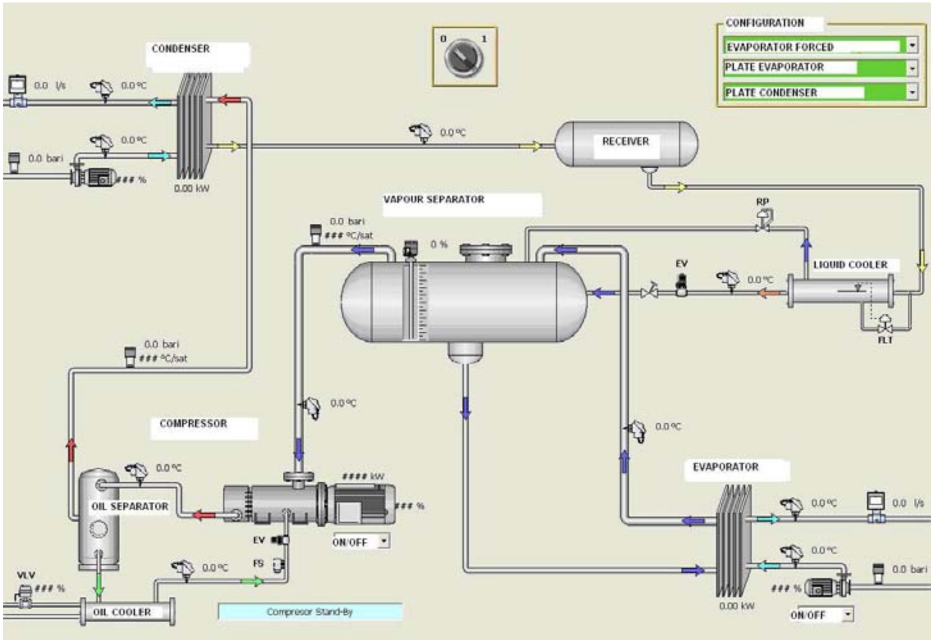


Fig. 12. Single stage mechanical vapor compression refrigeration system – schematic diagram

Fig. 13. Image of the refrigerating system

The single stage mechanical vapors compression refrigeration system using ammonia as a refrigerant is fully automated, so the refrigerating capacity may be adjusted depending on the cooled medium temperature required by the consumer. In addition, the experimental refrigerating system is equipped with a centralized data acquisition system allowing the remote control or adjusting of the working parameters in real time.
Research developed on this module refers to ammonia evaporation in plate heat exchangers, used for liquid cooling. Theoretical modeling of convective heat transfer coefficient represented the first research step. It concluded with calculation of convective heat transfer coefficient of evaporating ammonia in narrow spaces by using different correlations.
Simultaneously, an experimental investigation has been conducted and a measured values database was created. Further a comparison was made between experimental and theoretical data, aiming to confirm the correlations' validity for both geometry and given functioning conditions of the plate type evaporator. Experimental values were best modeled by **Kandlikar** correlation, applied for a vapour title of 0.5, in which case the relative error is of ±3% and to a lesser extent, by the same correlation, if applied for a vapour quality of 0.3.
The investigation concluded by recommending the use of the plate heat exchanger as an evaporator, in operating conditions similar to those used in the experiment.

4.2. Systems using R404A as a refrigerant

Technical features: refrigeration capacity: 18.0 kW, for -10.0°C evaporating temperature, +35.0°C cooling medium temperature and +20.0°C suction line vapor temperature. The system COP is 1.79. Heat rejection rate at condenser is 29.20 kW, for + 47.4°C condensing temperature.
This mechanical vapor compression refrigeration system uses R404A as a refrigerant is fully automated and includes one digital compressor of Copeland type with refrigeration capacity control depending on consumer heat demand.
The system is shown in Figure 14. As it may be observed from Figure 14, this is a mobile facility that can be moved in the laboratory space, next to the existing experimental air loop.

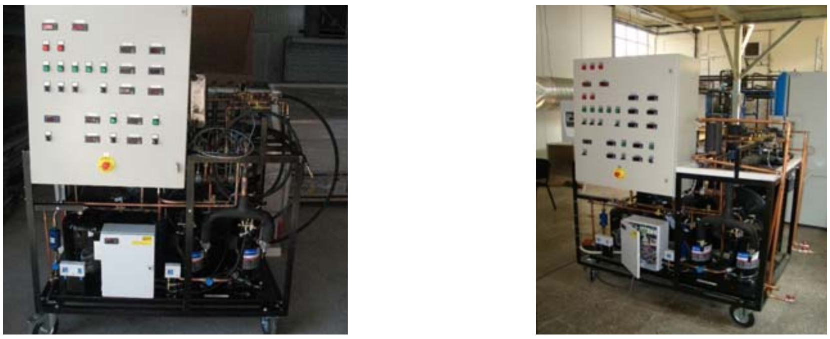


Fig. 14. Single stage R404A mechanical vapor compression refrigeration system

4.3. Systems using potential R22 substitutes

Theoretical investigation concluded that R422A, R424A, R417A and R428 working in refrigeration and heating pump systems show higher performance coefficients as compared to the following substitutes: R404A, R407C or R410A. As a consequence, an experimental study was performed using R417A as a substitute for R22. The experimental investigation was conducted on an air conditioning unit, manufactured by Carrier Company, model 42QNL009. The air conditioner has been designed to work with R22 as a refrigerant. The experimental stand is shown in Figure 15.

Air conditioner Thermographic view

Fig. 15. Experimental stand

Experimental research concluded that R 417A can successfully replace R22 for applications with evaporating temperatures under 3°C. This replacement does not require modification of the system, or oil change. Therefore the labor costs implied are minimal.

4.4. Climatic chamber for research and testing of equipment and materials at variable temperatures ranging from -75oC to + 180°C

The climatic chamber (ANGELANTONI type CH 2000C) shown in Figure 16 operates within the temperature range -75°C +180°C. The refrigeration system is of cascade type and uses R23 as a refrigerant for low temperatures and R404A for high temperatures. The climatic chamber capacity is 2040 liters and the air humidity range is 10% to 98%. The cooling capacity is 10.7kW and the heating capacity is 17.9 kW.

Fig. 16. Climatic chamber

4.5. Calorimetric room

The calorimetric room is shown in Figure 17. Its overall dimensions are: 4 x 4 x 2.8 m. The room has water-cooled walls by coils. Sensors (thermocouples and thermo resistances) monitor and control the inside air and surface temperature. Walls have been insulated. The calorimetric room complies with SR EN 442:2002.

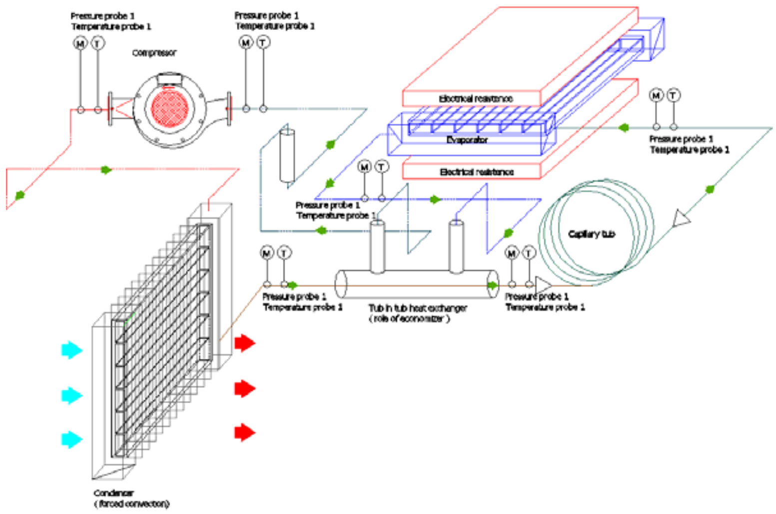
Fig. 17. Calorimetric room

This calorimetric room is used for testing purposes of: heat exchangers used for either cooling or heating various media as liquids or air, in natural or forced convection, without phase change, such as radiators, convectors, fan coil etc.; cabinets or split air-conditioners; two-phase heat exchangers, such as evaporators, condensers; refrigeration units (compressor and condenser); evaporation units (evaporator and fan); compact refrigeration systems (compressor, evaporator, fans, throttling valve).

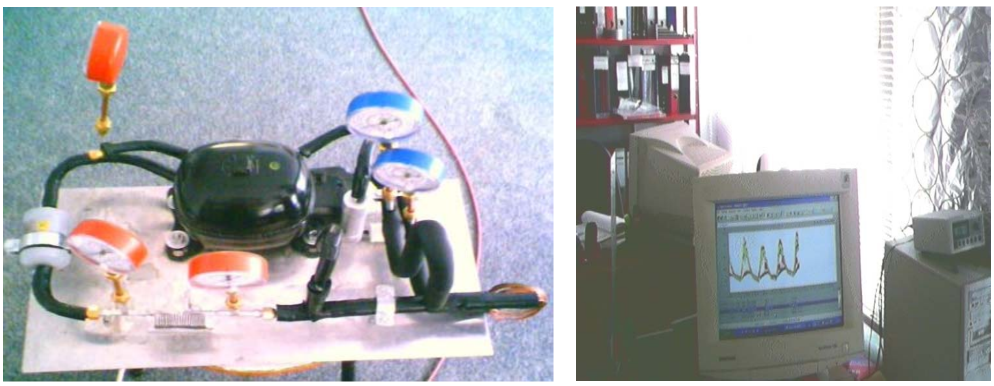
5. Refrigeration systems for micro electronic components

Micro electronic components of a computer produce a large amount of heat during operation. Thermal energy generated must be drawn out of the system to maintain all components within safe temperature ranges.

The refrigeration system specially designed to cool microelectronic components by mechanical vapor compression was assembled in June 2006 in the Laboratory of Thermodynamics and Thermal Equipment from the Technical University for Civil Engineering in Bucharest. The system is shown in Figure 18.



a) Schematic diagram



b) Overall view

Fig. 18. Refrigeration system for micro electronic components

This experimental stand allows investigation on cooling processes and identification of appropriate equipment (heat exchangers, compressors) for micro-refrigeration capacities, on miniaturization of the refrigeration system used, on refrigerant distribution inside mini-channel heat exchangers and assessment of the thermal performance of the miniaturized system.

Here are some of its technical features: hermetic compressor type TEE AZ 47 YT, displacement of 2.80 cm^3, refrigerating capacity ranging from 50 – 60W. Refrigerant used: R134a.

The refrigeration system for micro electronic components is characterized by low weight of 6.6 kg, compact size, high reliability and a low noise level and vibration.

Conclusions

- Ammonia has lately been considered as a viable alternative to the hydrocarbon refrigerants given its better thermodynamic properties and its harmful effect on the atmosphere. Unlike the CFCs, ammonia does not attack the protective ozone layer of the atmosphere and does not intensify the greenhouse effect.
- The research carried out by the Thermodynamic and Heat and Mass Transfer Department in the field of ammonia use in efficient refrigeration and air-conditioning systems dates back since 1965 and has gone through several stages. Refrigeration systems driven by non-conventional heat sources (solar energy, geothermal energy, and biogas) have been studied in the early stages.
- At present, the research is focused on efficient, compact systems, using “ice-slurry” and mini channel heat exchangers. These systems use mechanical compression and absorption as thermodynamics processes and ammonia-water solution as refrigerant.
- The research team of the Department for Thermodynamics and Thermal Equipment currently develops its work in national research projects.

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