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Study of the influence of ice fraction on heat transfer in comfort air-conditioning systems

Abstract of the PhD Thesis

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1. Introduction

This paper addresses a key issue in the context of energy efficiency and environmental protection, focusing on the influence of the ice fraction in the water-ice binary mixture on heat transfer in comfort air-conditioning systems.

The importance of efficient and sustainable air conditioning has become a global priority, particularly in the context of reducing energy consumption and greenhouse gas emissions. This paper aims to highlight the benefits of using binary ice in comfort air conditioning installations. By using this innovative solution, significant energy savings and increased thermal comfort can be achieved.

Modern air conditioning involves not only cooling the air, but also ensuring even temperature distribution, maintaining optimal humidity and reducing environmental impact. Conventional cooling technologies based on pollutant refrigerants (R134a, R404A, etc.) are increasingly regulated due to their very high global warming potential (GWP) and ozone depleting potential (ODS). In this context, alternative solutions, such as binary ice, are increasingly used in comfort air conditioning.

The main objective of the thesis is to analyze the influence of the ice fraction on heat transfer under various operational conditions compared to conventional systems using chilled water glycol. The hydraulic performance, energy efficiency, thermodynamic behavior and operational stability of the binary ice systems are followed.

2. Binary ice - general characteristics

Binary ice is a suspension of fine ice particles in a carrier liquid, usually water or water with additives (e.g. ethylene glycol or propylene glycol). This type of cooling medium is used to transport thermal energy and to store it in storage systems.

The advantages of using binary ice are multiple:

- High cold storage capacity due to the latent heat of ice;

- Easy transportation through standard pipelines with standard pumps up to 30% concentration;
- Output temperature constant and close to 0°C;
- Fast response to thermal load variations.

Disadvantages include:

- Risk of clogging in pipes if the ice fraction is too high;
- The need for careful control of temperatures and ice fraction;
- Possibility of mechanical abrasion on pumping equipment.

The optimum ice fraction used in real systems is between 10% and 30%, depending on the application, transportation distance and mode of operation. Physical properties, such as density and viscosity, vary significantly with this fraction, influencing plant sizing and equipment selection.

Binary ice allows the use of advanced energy strategies such as load shifting - producing cold during the night when energy is cheaper and using it during the day, especially when peak loads are at their highest.

3. Methods for generating binary ice

Binary ice generation involves the formation of a mixture of ice and carrier liquid by various technologies that ensure controlled particle sizes and a stable suspension.

The most commonly used methods are:

Scraped Surface Evaporators (SSE);

The production of binary ice by this method involves the use of a tube-in-tube heat exchanger ice generator. A refrigerant circulates in the space between the two tubes and an aqueous solution circulates inside. Ice formation occurs on the inner surface of the inner tube due to vaporization of the refrigerant to the outside. The ice thus formed, on the heat exchange surface, is continuously scraped off by a scraper system with a scraper screen. Ice scraping is necessary to prevent the formation of a thick layer of ice on the walls of the generator, which would introduce additional thermal resistance and could affect the heat transfer. Also, the continuous accumulation of a layer of ice on the generator walls would eventually lead to the rotation of the scraper blades being blocked and thus to the ice generator being completely blocked.

This method of generating ice requires a refrigeration plant with mechanical vapor compression in a single compression stage, consisting of a compressor, condenser, filter, lamination fan and vaporizer, as shown in Figure 1 . The vaporizer is represented by a tube-in-tube heat exchanger, which allows the generation of ice, which is why it is called an ice generator. In the annular space between the walls of the two tubes, the primary refrigerant (Freon or ammonia) is vaporized, taking heat from the binary solution which is transported through the inside of the ice generator tube by means of a scraper. The scraper system consists of a helical scraping device, usually a scraper bar, mechanically driven by a geared motor, which removes the ice from the inner surface of the vaporizer tube and transports it into the main stream.

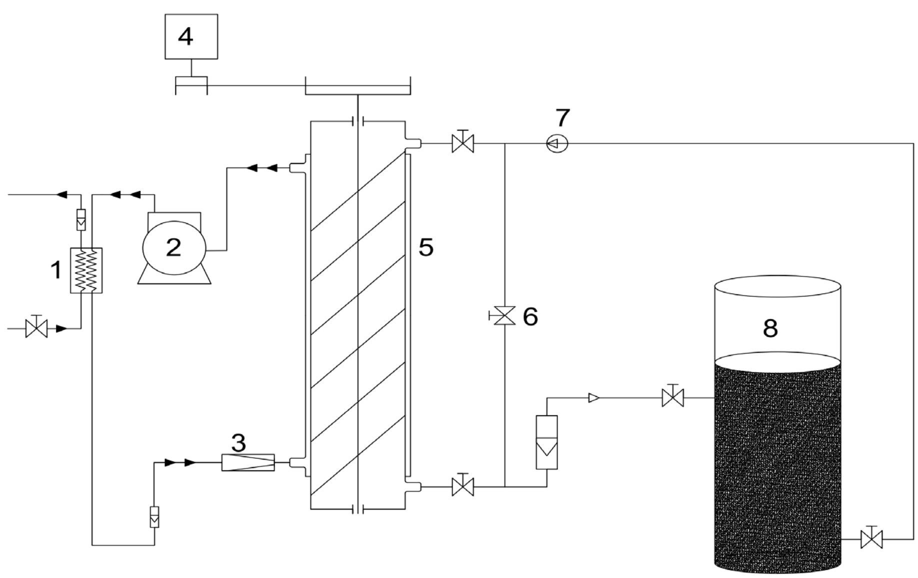


Figure1 Schematic of a binary ice plant scraped surface

The components of the scraped surface binary ice plant are: 1 - condenser; 2- compressor; 3- thermostatic control fan; 4- motor; 5- scraped surface vaporizer; 6- by-pass; 7- recirculation pump; 8- water-ice storage/accumulation tank .[75]

The experimental installation for the production of binary ice, shown in Figure 1 , is a system designed to generate a slurry composed of ice particles and liquid, known as water-ice. This slurry has applications in areas such as industrial process cooling, comfort cooling or refrigerated transportation.

Vacuum Ice Machine (VIM);

The generation of binary ice with vacuum vaporizers is based on the principle of the triple point of vacuum - freezing. The feed solution will be introduced into the vacuum chamber where the pressure is below the triple point of the solution[76] where part of the feed flow will then be converted to vapor. This process is considered to be adiabatic, meaning that the heat required for evaporation will be extracted from the remaining feed water and ice crystals may form. These ice particles are then mixed into the fluid and will result in a liquid of different viscosity called, binary ice, which can be pumped to the consumer or storage tank as required. To substantially increase the vaporization surface area the mixing chamber will be thermally agitated. Also for this purpose, spray introduction systems (sprayers) can be used resulting in intensification of the vaporization. Water vapor and non-condensible gases are discharged from the tank in such a way that the pressure is maintained at the initial value.

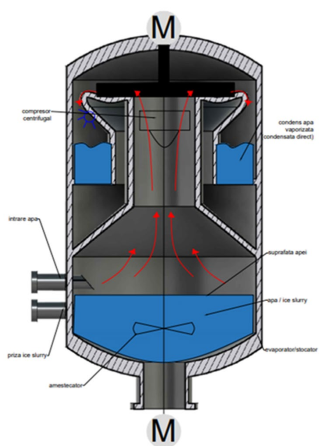


Figure2 Schematic of a water-ice generator with vacuum vaporizers

Fluidized Bed Evaporators (FBE).

In comparison, scraped surface vaporizers offer the best particle size control and are the most commonly used in industrial plants. Fluidized-bed vaporizers have high thermal efficiency but are more complex to construct.

The selection of the optimal method depends on the application, the required volume of ice, the desired efficiency and the operating and maintenance costs.

This method of obtaining the binary mixture is similar to that of the scrubbing shell evaporator (SSE), the solid particles in this case forming the local scrubbing system. The main advantage of this type of heat exchanger is that it has no heat transfer surface limitations. The whole above circuit can be operated with a classical recirculation pump. We can say that in comparison to the scraped surface evaporator (SSE), high velocities can be achieved in the piping of this type of evaporator without causing mechanical problems.

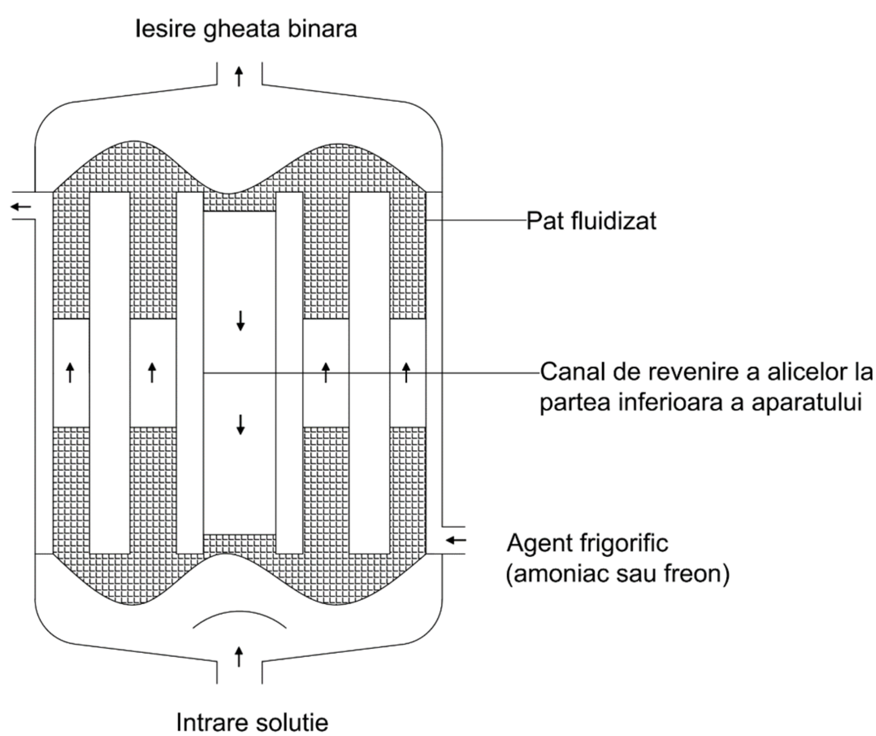


Figure3 Schematic of an ice generator with fluidized bed vaporizer

4. Influence of vaporization temperature on binary ice generation

Vaporization temperature is one of the key parameters in the binary ice formation process. The choice of the optimal temperature influences particle size, production rate, heat exchange efficiency and suspension stability.

Experimental studies have shown that a vaporization temperature between -9°C and -14°C gives the best results for efficient particle formation. Below this value, the overall efficiency of the refrigeration cycle decreases due to high power consumption. At temperatures higher than -8°C, the ice fraction obtained is insufficient to ensure optimal plant operation.

The performance versus vaporization temperature curve is non-linear, and the choice of the operating point has to take into account thermal performance as well as power consumption, cycle time and binary mixture stability.

This chapter substantiates the importance of the correct definition of the working point in binary ice based air conditioning systems, being closely related to the choice of refrigerant and the optimal design of the vaporizer.

5. Methods to avoid ice particle clumping

One of the main risks in the operation of binary ice plants is the agglomeration of ice particles, which can lead to clogging of pipes, reduced heat transfer efficiency and damage to equipment.

To avoid this, the following methods are used:

Continuous stirring in storage tanks: helical, paddle or recirculating stirrers ensure that the ice particles are kept in homogeneous suspension;

Mixture flow at high velocities: Maintaining a flow velocity above 1.5 m/s in the pipes prevents particles from settling on the walls and agglomeration;

Use of specialized slurry pumps: open impeller pumps or centrifugal pumps with solid particle tolerance, which do not destroy ice and maintain slurry integrity;

Avoid tight bends and narrow cross-sections: piping routes should be designed so as not to favor fluid stagnation or phase separation;

Pressure and flow monitoring sensors: integration of an automatic control system that detects deviations from normal parameters and corrects the plant operation in real time;

Ice stabilizing additives: in certain cases, dispersing agents or stabilizers may be added to improve the rheological behaviour of the mixture.

Implementing these methods significantly increases plant reliability, reducing the need for maintenance interventions and increasing equipment lifetime. It also ensures predictable and safe operation under varying thermal load regimes.

6. Influence of ice fraction on pressure drop

The ice fraction has a direct impact on the hydraulic behavior of the binary mixture and, consequently, on the pressure drop in the distribution network. Increasing the percentage of solid particles leads to significant variations in viscosity, density and flow regime.

Up to a fraction of 20-25%, the head losses remain close to those of cold water, provided a minimum flow velocity is maintained. In this zone, the behaviour of the suspension is relatively predictable and the flow remains turbulent, ensuring good transport and homogenization.

The major challenge associated with the operation of water-ice mixing plants is to ensure the homogeneity of the binary mixture, both in the storage tank and in the distribution system piping. Although indispensable, the mixing of the water-ice solution in the storage tank can be quite energy intensive. The literature offers a number of solutions to prevent particle agglomeration and stratification of the ice particles: due to the difference in density between the ice particles and the aqueous solution with which they are in contact.

A possible solution to counteract this phenomenon has been experimented by Meil et al. who used intermittent mixing. One solution to the problem may be to recirculate the water-ice mixture through the outside of the tank and mix it with a volumetric fraction of denser ice extracted from the bottom of the tank.

1.1.1 Tube pressure drop.

The pressure drop (ΔP) in a tubing system is an indicator of the resistance to flow that a fluid encounters as it moves through the tubing. This resistance to flow can be influenced by several factors, including the viscosity of the fluid, the flow velocity, the diameter and roughness of the inside of the tube, and the flow regime (laminar or turbulent).

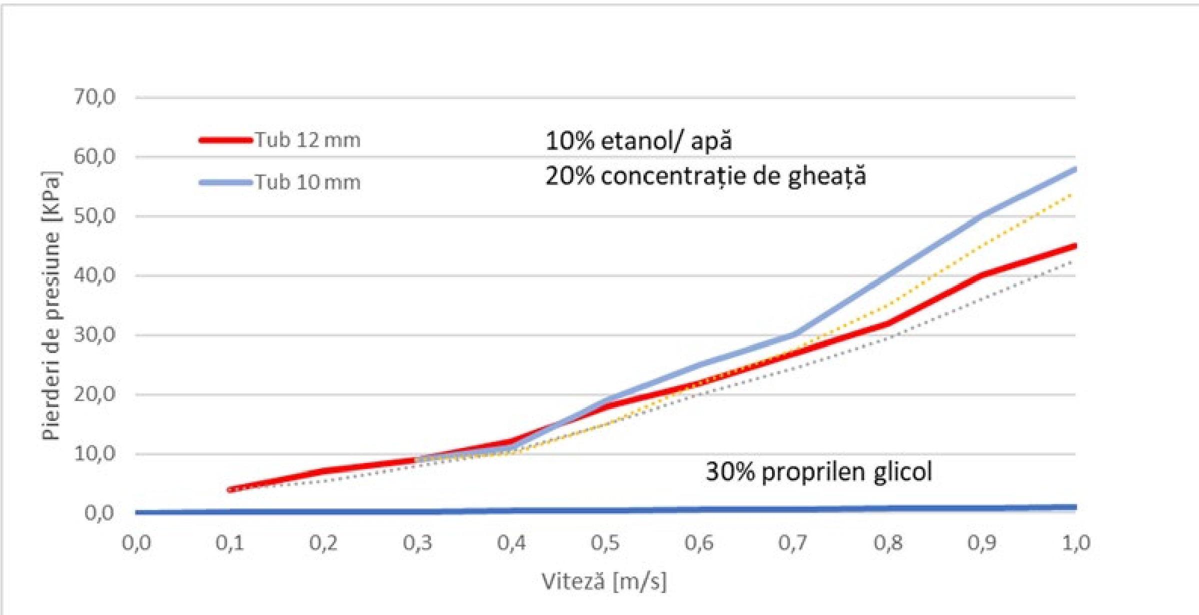


Figure4 Comparison between head loss in single-phase flow and head loss in two-phase (water-ice) flow

Head losses as a function of ice fraction and flow velocity.
An exponential increase in pressure drop is observed for fractions above 30%, especially at low velocities (< 1 m/s), where segregation and particle accumulation tendencies occur in low flow areas.

To maintain system performance, it is necessary:

- Proper sizing of pipe diameters;
- using pumps with characteristics compatible with two-phase suspensions;
- avoid long routes with large differences in level or many bends;
- automated differential pressure control to maintain uniform flow.

- The findings show that although the use of higher ice fractions brings thermal benefits, they imply a hydraulic cost that needs to be carefully managed through proper design and operation.

7. Heat transfer in air conditioning systems with binary ice

Heat transfer is the main function of using binary ice in air conditioning systems. The thermal efficiency of this working medium is far superior to water or glycol solutions, due to its high energy absorption capacity by melting solid ice particles.

The heat transfer process occurs simultaneously by two mechanisms:

- convection between the carrier liquid and the exchange surface;
- the melting of ice particles on contact with the exchanger walls, which involves the transfer of latent heat from the ice.

This dual mechanism leads to a significant improvement in the overall heat transfer coefficient. In the experimental studies, values 2 to 4 times higher than water or glycol solution have been recorded.

Variation of air temperature as a function of the ice fraction used in the cooling coils. The graph shows faster and more efficient cooling for fractions of 20-30%, with air outlet temperatures below 12°C at constant flow and initial temperature conditions.

Other advantages of using binary ice for heat transfer include:

- higher stability of the outlet temperature, which increases thermal comfort in the spaces served;
- the possibility of operating at low flow rates and low temperatures, which reduces the size of the installations;
- reducing the ON/OFF cycles of compressors, contributing to longer equipment life.

However, the design of heat exchangers must take into account the increased viscosity of the mixture and the risk of ice films on the walls, which can reduce efficiency if not properly managed. The choice of a turbulent flow regime and precise control of the ice fraction are essential to achieve optimum heat transfer.

8. Thermodynamic and thermophysical properties of binary ice

The thermodynamic properties of binary ice are essential in the sizing and efficiency of air-conditioning systems using it. These properties depend mainly on the ice fraction, the temperature and the composition of the carrier mixture.

The most relevant properties include:

- **Specific heat**

$$c_p = \frac{h(T) - h(T + \delta T)}{\delta T}$$

The specific heat of conventional single-phase intermediate refrigerants is about eight times lower than that of binary ice. As a result, their diameter and velocity inside the pipes can be reduced by about half.

- **Thermal conductivity**

$$\lambda = \lambda_l * \frac{1 + 2 * f_{vol} * y}{1 - f_{vol} * y}$$

where:

λ = thermal conductivity of ice, [W/mK];

λl = thermal conductivity of the solution, [W/mK];

f vol = the calculation formula for the volumetric fraction of ice is:

$$f_{vol} = \frac{f}{f + (1 - f) * \frac{\rho_g}{\rho_l}}$$

$$y = \frac{1 - \frac{\lambda_l}{\lambda_g}}{2 * \frac{\lambda_l}{\lambda_g} + 1}$$

where:

y = coefficient calculated after Eucksen - Hansen;

λl = thermal conductivity of the solution, [W/mK];

λg = thermal conductivity of ice, [W/mK];

The usual methods used to measure thermal conductivity are inadequate because any slight heating reduces the concentration of binary ice.

There were no references in the literature consulted so far to experimental determination of thermal conductivity.

So far, the models that have been studied and used are based on the thermal conductivity of the liquid phase, which is influenced by the thermal conductivity of the binary mixture.

Reid[104] provides a commonly used relation:

$$\boldsymbol{\lambda_l = f * \lambda_{l1} + (1 - f) * \lambda_{l2} - 0,72 * f * (1 - f) * (\lambda_{l2} - \lambda_{l1}) \quad \lambda_{l2} > \lambda_{l1}}$$

Ordóñez-Miranda et al.[105] applied Maxwell's analogy between the electric field and the temperature field to establish a relationship for calculating the thermal conductivity of binary ice (in the liquid-solid biphasic state).

The experiments carried out by the authors were based on an analogous model developed by Antononi (1985) for a mixture of coal and water:

$$\boldsymbol{\lambda = \lambda_l * \frac{2*\lambda_l + \lambda_g - 2*\varphi*(\lambda_l - \lambda_g)}{2*\lambda_l + \lambda_g + \varphi*(\lambda_l - \lambda_g)}}$$

where:

λ = thermal conductivity of binary ice, [W/mK];

λl = thermal conductivity of the solution, [W/mK];

λg = the thermal conductivity of ice , [W/mK];

ϕ , β , γ = calculation coefficients

Vl = volume of liquid in the mixture

Vg = volume of ice in the mixture

Berg (1995, 1999), developed a correlation based on Jeffrey's model[106] which also took into account the thermal interaction between ice particles:

$$\boldsymbol{\lambda = \lambda_l * [1 + 3 * \varphi * \beta * (1 + \varphi * \beta * \gamma)]}$$

$$\boldsymbol{\varphi = \frac{V_g}{V_l};\ \beta = \frac{\alpha-1}{\alpha+2};\ \alpha = \frac{\lambda_g}{\lambda_l};\ \gamma = 1 + 0,25 * \beta + \frac{3*\beta}{16} * \left(\frac{\alpha+2}{2*\alpha+3}\right)}$$

Equivalent specific heat: changes with the proportion of solid phase, averaging 2.2-2.8 kJ/kg-K for fractions between 20-30%;

Enthalpy: gives a picture of the total energy available in the melting and cooling process;

The mass enthalpy of a water-ice mixture can be determined by summing the mass enthalpies of the two main components: the pure ice and the liquid mixture (water-additive solution), all measured at the same temperature.

The mathematical relationship that describes this calculation is as follows:

$$\boldsymbol{h = f_g * h_g + (1 - f_g) * h_l}$$

where:

fg = the mass fraction of slurry [%];;

hg = mass enthalpy of ice, [J/kg];

hl = mass enthalpy of the aqueous solution, [J/kg].

The proportion of ice in such a mixture is directly influenced by the initial mass concentration of the added substance (additive) in the water and the final concentration of the additive in the amount of liquid remaining after ice formation. These concentrations are determined by the solid-liquid phase diagram.

Assuming that the enthalpy of mass of pure water and pure additive at 0°C is zero, the specific enthalpy of ice can be calculated using the following relation.

$$\boldsymbol{h_g = c_{pg} * t - r_s}$$

where

r_s = the latent heat of melting of ice at 0°C (333000 J/kg).

The Bel&Lallemand relation[100] is used to calculate the mass specific heat of ice at 0°C and is of the form :

c_{pg}= 2.1162+ 0.0078· t, [J/(kg K)]

The mass concentration of the additive and the temperature of the water-ice mixture have a direct effect on the enthalpy of the liquid phase *hl* *hl*= · (cr ,T), the relation for its calculation being

$$h_l = c_{pl} * T$$

in which:

c_{pl} = mass specific heat at constant pressure of the aqueous solution.

The specific enthalpy of the water-additive mixture can be obtained from specific tables or nomograms, the values being determined as a function of the volumetric or mass concentration of the additive and as a function of the temperature of the mixture. The enthalpy of a water-ice mixture is influenced mainly by the proportion of ice present, and to a lesser extent by the heat capacity of the water-additive mixture.

Viscosity: increases exponentially with ice fraction and directly influences the flow regime.

- **Dynamic viscosity** (after Thomas)[107]

The viscosity of binary ice is determined by a number of factors, including the average volume fraction of ice in the binary mixture, the average velocity, the tube diameter, the ice particle size, and the thermophysical and transport properties of the heat transport solution.

Calculating the viscosity of two-phase fluids is a complicated process, especially when dealing with a liquid-solid mixture such as binary ice. It has to be taken into account that the distribution of the ice volume fraction in the liquid is never uniform but heterogeneous. Under these circumstances, the rheological properties of the ice in suspension are affected and have an impact on the transport properties of the fluid. Because of this, depending on the working conditions, the water-ice mixture can act as a Newtonian fluid, or not. According to experiments carried out in the laboratory[10, 51] , the water-ice mixture behaves like a Newtonian fluid at medium velocities and low volume fractions. The viscosity is influenced by both the average velocity and the tube diameter, in addition to the water-ice mass fraction, which increases with increasing mixture velocity. It follows that binary ice behaves as a Bingham fluid or as a Nenewtonian fluid. The viscosity of the water-ice mixture increases with tube diameter at lower average velocities.

For the design of systems using binary ice as a secondary agent, it is essential to take into account the rheological behavior of binary water-ice mixtures. This behavior can be as a Newtonian fluid until the ice volume fraction reaches a critical value or a certain threshold. This is the reason why the viscosity of the water-ice mixture varies with time, because the size of the ice particles in the mixture changes with time. Experiments conducted by Thomas[107] have shown that different particle sizes of the water-ice particles in the mixture impact the viscosity at water-ice volume fractions less than 6%. The influence of particle diameter increases with increasing ice-ice volume fraction. Consequently, particle size is extremely important if the flow becomes heterogeneous. This is especially true in situations where the mean mixing velocity is extremely low and there is a risk that the ice particles may stratify at the top. The influence of interaction forces is greater in heterogeneous mixture flow than in homogeneous mixture flow. Due to these forces, the local viscosity value of the water-ice mixture at the top increases rapidly, thus influencing the average viscosity value of the mixture.

For example, Einstein's equation can be used to calculate the dynamic viscosity of a two-phase water-ice mixture:

$$\boldsymbol{\eta = \eta_l * (1 + 2,5 * f_v)}$$

in which:

ηl = the dynamic viscosity of the liquid consisting of water and additive;

fv = the volume fraction of ice in the binary mixture.

Dynamic viscosity of the water-additive solution (propylene glycol, ethylene glycol or ethanol), ηl, can be found in textbooks or specialized nomograms, depending on the mass concentration of the additive used and implicitly on the temperature of the aqueous solution.

The ice volume fraction, fv , is calculated with the formula:

$$\boldsymbol{f_v = f_g * \frac{\rho}{\rho_g}} \quad ( )1$$

In addition, the dynamic viscosity of the water-ice mixture can also be easily calculated using the Jeffrey equation:

$$\boldsymbol{\eta = \eta_l * (1 + A * f_v)}$$

where 2,5<A<10

When it comes to calculating the local viscosity value for a heterogeneous flow, neither the Einstein nor the Jeffrey equations[106] take into account the interaction between ice particles. This is essential for low average velocities combined with high ice volume fractions.

From the above, it follows that the Jeffrey equation simulates the flow of the homogeneous suspension, which is represented by the two-phase mixture known as water-ice; this happens at high velocities, so the effect of the interaction between the ice particles is insignificant.

Other experiments have shown that at high two-phase mixing velocities and low ice volume fractions, e.g. less than 10% of the mean value, the viscosity of the binary mixture is independent of the mean binary ice velocity, as in Newtonian fluids. However, the viscosity of the water-ice mixture increases rapidly as the mixture velocity decreases and the ice mass fraction increases.

Homogeneous two-phase homogeneous flows, whose viscosity depends only on the average water-ice volume fraction, were created by binary mixture velocities of about 2 m/s,; therefore, the viscosity can be obtained using the Thomas equation :[107]

$$\boldsymbol{\eta} = \boldsymbol{\eta_l} * (\mathbf{1} + \mathbf{2,5} * \boldsymbol{f_v} + \mathbf{10,05} * \boldsymbol{f_v^2} + \mathbf{0,00273} * \boldsymbol{e^{16,6 * f_v}})$$

in which:

μ = viscosity of the water-ice mixture, [N*s/m^2];

μl = the viscosity of ice in the liquid state, [N*s/m^2];

fv = ice volume fraction, [%].

In addition, experiments have shown that ice particle size has no influence on the viscosity of binary ice once the flow is ensured to be homogeneous.

Ice particle size and tube diameter reduce the viscosity of the water-ice mixture by about 3 to 6%. This only happens if the average velocity of the water-ice mixture decreases, which can lead to agglomeration of ice crystals at the top of the tube.

For ice volume fractions greater than 15%, the Thomas equation[107] indicates higher values than measured.

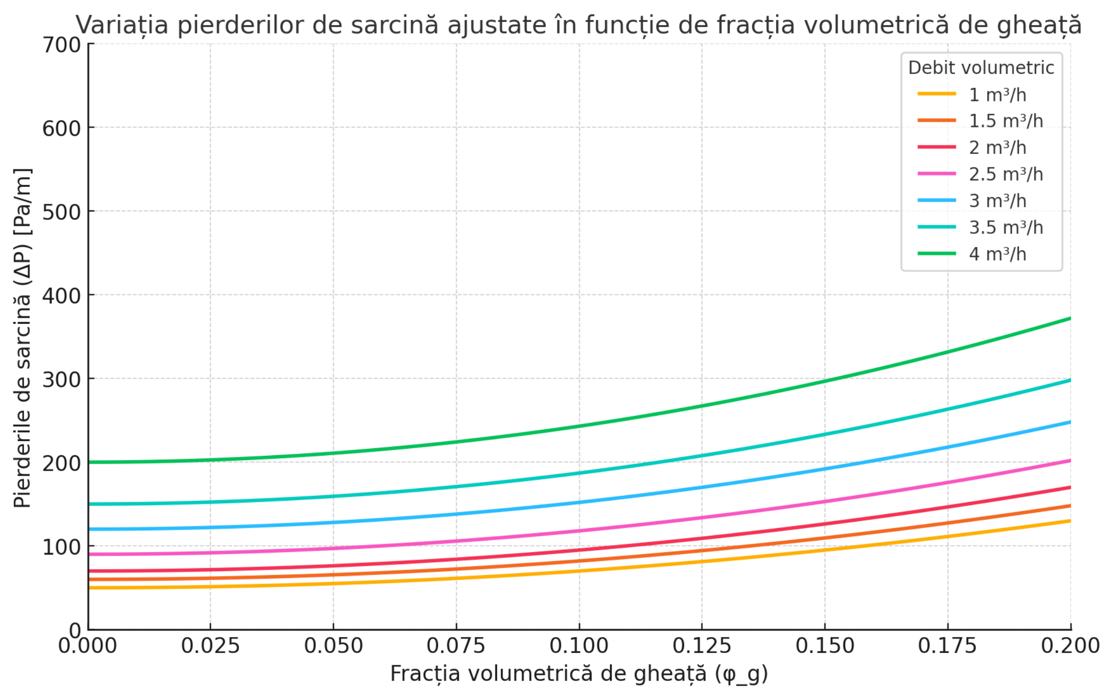
- **Miscarriages**

The charge losses of the five types of intermediates are approximately equal at low ice concentrations, ranging from 10 to 15%. Calcium chloride and magnesium chloride solutions have higher pressure losses than ethylene glycol, ethanol and propylene glycol solutions at ice concentrations above 15%. Consequently, the concentration of the solutions was chosen to guarantee an identical freezing point in each of the five cases.

The ethanol-water solution is responsible for the lowest charge loss. Microscope photograph of the ice particles that were created in each of the five different solutions showing that the ice particle sizes remained the same in each of the cases. Therefore, they could not indicate that are different pressure losses are produced by differences in ice particle sizes.

Also from the microscopic analysis it was observed that, regardless of the type of ice generator used, the ice particles have the same size, if the freezing condition of the solution is the same.

A diagram showing the variation of the pressure drops as a function of the ice volume fraction in the two-phase mixture was created by Bel (1999)[108] . The rheological behavior of the mixture changes for ice volume fractions between 10 and 15%, as shown in the figure.



Variation of pressure drop with ice volume fraction

This leads to a linear increase in the charge drop, (ξ), according to the relation:

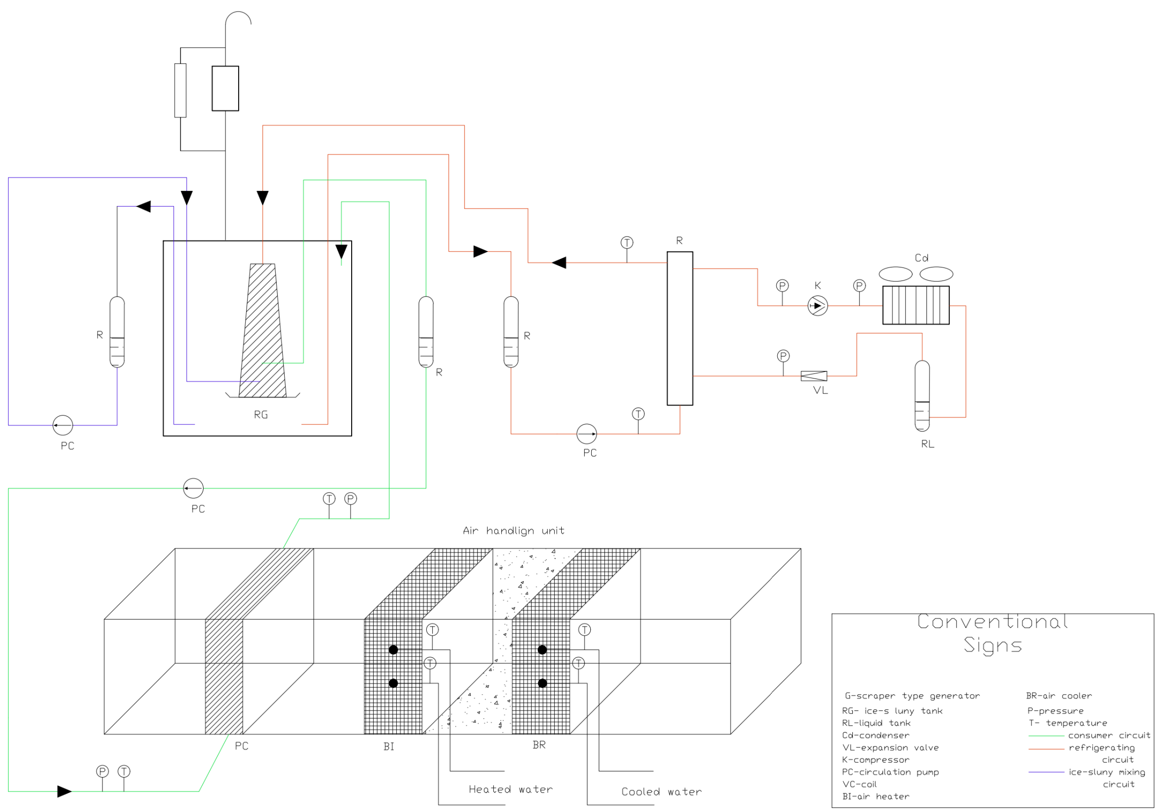
$$\xi = \frac{\Delta p}{\frac{\rho^2 * w}{2}} * \frac{D_h}{L}$$

Variation of enthalpy and viscosity with ice fraction.
The graph shows two main curves: one shows the variation of total enthalpy as a function of ice

fraction, and the other the dynamic viscosity curve. A gradual decrease in enthalpy is observed, concomitant with an exponential increase in viscosity above the 30% ice threshold.The behavior of an experimental refrigeration cycle with R448A was analyzed, in which binary ice was used as an intermediate medium. The results showed an overall efficiency improved by 17% compared to classical systems, due to the recovery of latent melting energy during the batch mode.

9. Experimental facility used in the research

To validate the theoretical hypotheses and analytical conclusions, an existing experimental facility at the UTCB laboratory was used for the production and testing of binary ice under controlled conditions.



2D schematic of the experimental binary ice generation refrigeration plant

Description of the main components of the installation:

- SSE (Scraped Surface Evaporator) binary ice generator with a cooling capacity of 7 kW;
- Buffer tank of 1000 liters, equipped with axial agitator to maintain the homogeneity of the suspension;
- Coaxial heat exchanger, used to extract cold energy from the mixture;
- Air cooling coil equipped with inlet and outlet temperature sensors;
- Recirculating pumps with automatic frequency control;
- Sensors for measuring pressure, flow, temperature;
- Automation system with Moeller PLC and HMI interface for real-time control and monitoring.
- Programmable Logic Controller (PLC - Moeller Logic Controller) - this device is the brains of the automation system, managing the control logic for the entire plant. It has digital and analog outputs to control pumps, compressors and condenser fans. It integrates temperature and pressure sensors, collecting temperature and pressure data to control refrigeration processes.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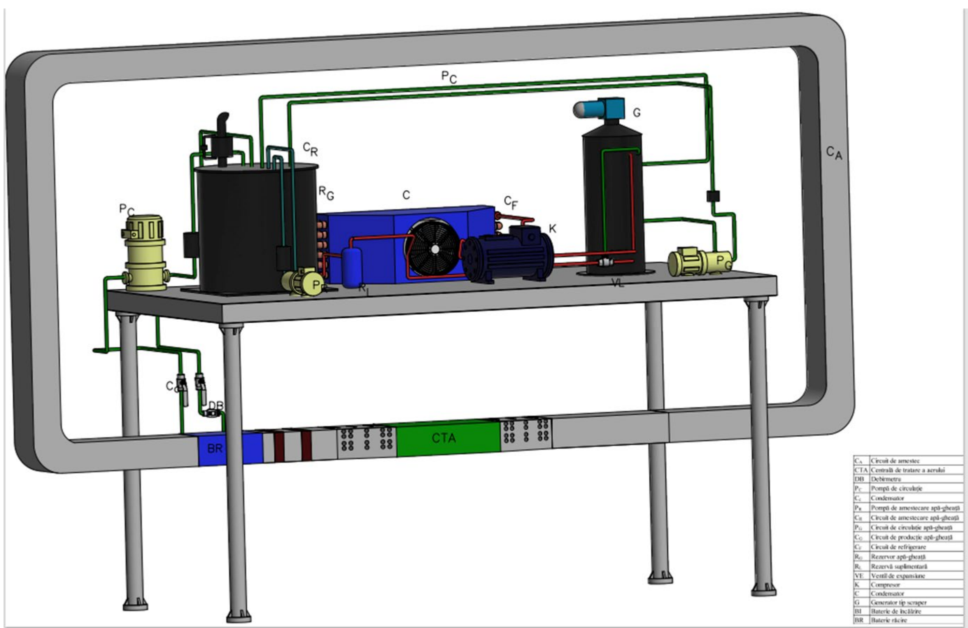
- Protection modules and relays. Modular relays are visible at the top right of the panel we provide protection for pump or compressor motors against overloads, short circuits or other faults. Fuse devices in the upper left provide additional protection for electrical circuits.
- Digital temperature displays. The two Dixell type controllers (bottom) show the

temperatures in the ice-making refrigeration plant as well as the temperatures of the binary mixture in the 1000 liter tank. These controllers are connected to PT100 temperature sensors at different points in the plant: one for the binary ice tank and the second for the water-ice circuit to the consumer.

- Functional scheme of the experimental installation for the generation and utilization of binary ice.
  The schematic shows the complete route of the refrigerant and the binary ice mixture, highlighting the measurement points, heat exchange and ice fraction control.



3D scheme of the experimental stand used in the research

Photo of the actual stand used.

The experimental stand used allows:

- testing the variation of the yield as a function of operational parameters (vaporization temperature, ice fraction);
- observing charge losses as a function of paths, velocities and proportion of solid particles;
- Analysis of the thermodynamic behavior of the indirect cooling cycle with binary ice;
- validation of the theoretical models developed in the paper.

Through this installation, duty cycle data were collected in various configurations. This formed the basis for assessing the system performance and the influence of ice fraction on overall efficiency.

10. Results and discussions

Analysis of the experimental data allowed to evaluate the performance of the binary ice system in different operating regimes.

The main results highlighted are:

- Increase overall efficiency by 20-25% compared to traditional solutions;
- Reduce the time needed to reach target temperatures in cooling coils by 30-40%;
- Coolant temperature stability at the exchanger outlet, even under variable load conditions;

- Acceptable load losses up to 30% ice fractions and speeds above 1.5 m/s.
- Refrigeration cycle efficiency as a function of ice fraction.

A significant increase in yield is observed between 15% and 30% ice fraction, with a plateau at values above 30% due to increased viscosity and decreased useful flow.
Evolution of the air temperature at the outlet of the battery as a function of exposure time and type of coolant.

The interpretation of these results confirms the advantages of the use of binary ice in comfort air conditioning and allows to outline sizing and operation recommendations for real applications.

11. Conclusions and proposals for further research.

The experimental investigations presented in this thesis have led to the following conclusions:

- for the same volumetric fraction of ice in the mixture, the refrigerating capacity increases with increasing flow rate of the water-ice mixture feeding the air-cooling battery;
- The cold demand at the consumer was validated experimentally;
- this averaged 5.17 kW for an ice volume fraction of 15.00%;
- 5.42 kW for an ice volume fraction of 16.00%;
- 5.74 kW for an ice volume fraction of 17.00 %, and the air flow rate in this analyzed situation being constant $Qaer = 3000\ m^3/h$.

Concerning the thermophysical and transport properties of binary ice it should be emphasized that a number of hypotheses have been accepted related to:

- No change in ice particle size over time;
- Behavior of the binary mixture as a homogeneous mixture;
- Absence of interaction forces between particles, i.e. ignoring agglomeration tendencies in the storer, consumer and through the pipes.
- Dissemination of experimental versus theoretical results in unacceptably wide intervals.

With regard to the experimental problem, there are a number of aspects that are difficult to control, such as:

- Conducting a forced mass fraction mode of operation at the outlet of the heat exchanger, including total melting of ice particles;
- Prevent particle agglomeration inside the storage tank;
- Homogeneous flow of the binary mixture in the distribution and supply network to the water-ice consumer;
- Superheating of the liquid phase of the mixture at the outlet of the heat exchanger.

Concerning the mathematical modeling of the heat and mass transfer of the water-ice mixture circulating through different types of heat exchangers, it must be emphasized that the available criterial equations model the phenomenon in a rather punctual manner, that is, limited by excessively particular, specific conditions, both of constructional and functional type. This type of modeling drastically narrows the range of application of these equations in real calculations of operation and sizing of these types of air conditioning systems.

This is the context in which, I believe, experimental research on modeling the heat and mass transfer of the water-ice mixture through different types of heat exchangers, pipes and comfort air conditioning circuit equipment, as well as for obtaining universally valid criteria equations, is still highly topical.

As an advantage we can say that for the studied ice fractions it is not necessary to modify any equipment or parameter of the hydraulic circuit of the water-ice mixture transportation in relation to the water-cooled water.

Another advantage of using binary ice is that the heat transfer takes place at quasi-constant temperature, which substantially improves comfort. The refrigerating capacity transported per unit volume increases as the ice fraction increases and thus it is possible to reduce the cross-section of the transport piping and the heat exchange surface area at the consumer from the design stage, while obtaining the same refrigerating capacity.

The installed cooling capacity for these systems is much reduced because it uses the latent heat storage of the water-ice mixture during no-load hours and its release when needed during peak load periods.

In today's context of sustainability and increased energy efficiency, the use of refrigerant type R 448A reduced the global warming potential impact by about 3 times, from a GWP of 3922 to a

GWP of 1387, and the working pressure in the refrigeration plant was also reduced by about 6%. This retrofit reduced both the carbon footprint and the electricity consumption of the compressor, achieving the same payback.

My personal contribution consisted in promoting and carrying out the replacement of the highly polluting refrigerant R 404A with the refrigerant R 448A which has multiple advantages, proven during the PhD thesis. The comparative analysis between the two refrigerants R 404A and R 448A respectively, presenting the advantages and disadvantages of using the latter.

Automation of the water-ice mixture circulation pump by introducing a variable frequency drive, with which we controlled very precisely the frequency and flow rate of the water-ice mixture and also protected the pump from possible overloads.

Repair of the geared motor of the ice-maker and making it airtight again. Re-tightness of the refrigerating circuit, replacement of the dehumidifying filter. Adjusting the overheating in the refrigerating circuit where we took into account the 6 degrees Celsius slip of the new refrigerant. Adjusting the additive concentration to lower the freezing point.

Browse, analyze and systematize information of many scientific papers read in the field of thermotechnical, mechanical engineering and legislation.

Active participation in scientific conferences, seminars and congresses in the field of comfort air conditioning in the USA, Turkey, China, Denmark, Republic of Moldova, Italy, Serbia and Romania, where we disseminated the advantages and disadvantages of using water-ice mixtures in air conditioning systems.The results presented in this paper convincingly highlight the potential of binary ice as an efficient cooling agent in air conditioning systems. The use of this technology leads to improved energy performance, reduced cooling time, and increased operational flexibility of the installations.

Summary of conclusions and research directions.

Aspect rated	**Conclusion**	**Research proposal**
Heat transfer	Improved by up to 4x over water	Advanced CFD studies on FX
Energy efficiency	+25% compared to classical solutions	Integration with renewable sources
Stability and control	Hi, if the fraction and flow rate are optimized	Adaptive systems with artificial intelligence
Operating costs	Lower in the long term	Life Cycle Assessment (LCA)
Scalability	Possible in industrial applications	Studies on large-scale installations

Proposals for future developments:

- Integration of binary ice in hybrid systems (air conditioning + energy storage);
- Using smart sensors to control ice fraction;
- Adapt the technology to Mediterranean and tropical climates for maximum efficiency;
- Extending applications to the food industry, IT, agro-industry or the medical field.

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