Design optimal of refrigeration insulations

Ioan Sarbu, Emilian Stefan Valea, and Gabriel Ostafe

Abstract—Economic operation with minimal energy consumption and low costs of a cooled room or a refrigerant piping system depends largely on the quality and thickness of their insulation. The classical method of insulation rating for refrigeration systems is based on respect of the condition to prevent condensation of water vapours in the air on the surface of insulation or on limiting heat gain, but rarely leads to optimum in terms of a technical and economic criterion. In this paper are described some types of insulation for refrigeration applications and is developed a rating optimization model of these insulations with a high level of generality. It uses multiple dynamic optimization criteria simple or compound, which better reflects the economic and energy complex aspects, present and future. Based on this model were elaborated two computer programs implemented on PC microsystems. Numerical examples will be presented to demonstrate the accuracy and efficiency of the proposed optimization model. These show the good performance of the new model.

Keywords— Cooled rooms, Refrigerant piping, Insulation rating, Optimization model, Comparative analysis.

I. Introduction

The role of refrigeration system insulation is to reduce heat flow to cooled spaces or to cold devices and pipes in which the refrigerant temperature below ambient temperature (free air, soil or neighbouring rooms). Therefore, refrigeration insulation is commonly used to reduce energy consumption of refrigerating systems and equipment.

Economic operation of a cooled room or a cold pipe depends largely on the quality and thickness of their insulation. Hence the proper selection importance of the insu-lation material and rating of their refrigeration insulations, leading to judicious use of investment funds, to normal operation with minimal energy consumption and low costs.

Cellular glass, flexible elastomeric, mineral wool, polyisocyanurate, and expanded or extruded polystyrene are insulation materials commonly used in refrigerant applications.

The classical method of insulation rating for refrigeration systems is based on respect of the condition to prevent condensation of water vapours in the air on the surface of insulation, but rarely leads to optimum in terms of a technical and economic reason. In case of flat surfaces is used heat transfer equation which admits a heat gain so that neither results too thick expensive insulation, nor very high cool consumption. In specialty literature [2], [11] are recommended thicknesses for refrigeration insulation based on condensation control or for limiting heat gain.

The most economical insulation thickness can be determined by considering both initial costs and long-term energy savings. Optimal computation of the insulations applied to cooled rooms and to cold pipes based on economic criteria of minimum total life-cycle cost leads to insulation thickness that applied in practice become incorrect at some point after the execution, because price evolution in time. The energy costs are volatile, and a fuel cost inflation factor may increase more quickly than general inflation.

In this paper is developed a computational model of the optimal thickness of these insulations, with a high level of generality. This model uses multiple dynamic optimization criteria simple or compound, which better reflects the economic and energy complex aspects, present and future. Based on this optimization model are elaborated two computer programs implemented on PC microsystems.

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II. Types of Insulation for Refrigeration Applications

Refrigeration systems cover a broad spectrum of application temperatures and environments. But they all face the same issues relating to both condensation control and moisture. Since moisture is a good thermal conductor, its presence in an insulation system is highly detrimental. Unlike hot systems, where marginal insulation may result in increased energy use (and added cost), refrigeration systems face condensation, which often leads to complete system failure. Even with today's high energy costs, the design thickness in most refrigeration applications is dictated by what is needed to prevent condensation, rather than by economic payback.

Refrigeration systems typically operate in the range of –5°C (for Freon systems) to as low as –45 °C (for ammonia systems). They can use a variety of refrigerants and fluids in addition to Freon and ammonia, including glycol, brine, and other specialty fluids. Copper, iron, stainless steel, or other piping materials may be used to carry the cooling medium. Typical applications include those in supermarkets, beverage–dispensing lines, chillers, and food processing, freezing, and storage facilities. Other applications include those at ice rinks and various unique applications. All of these applications share common concerns regarding condensation control and long-term reliability, but they also have particular issues with installation, required thickness, and the environmental conditions in which they operate.

Reliability should be the primary concern when considering the design and installation for any application. Design must consider factors including the application temperature, environmental considerations, consequences if a failure occurs, and expectations of the job by the owners (longevity of the system, aesthetics, etc.). The following are some important features of the insulation in various refrigeration applications:

– thermal conductivity;
– water vapor transmission (WVT) properties;
– water absorption properties;
– coefficient of thermal expansion;
– moisture wicking.

There are recommended the following insulation materials for refrigeration applications [2]: cellular glass, closed-cell phenolic, flexible elastomeric, polyisocyurante, and polystyrene. All of these materials are closed-cell foam materials, which means they will have good WVT and low water absorption characteristics.

In all cases, the entire system (seams, butt joints, and termination points) must be completely sealed with adhesives to protect against air intrusion into the system, which would carry moisture and result in condensation between the cold pipe and the insulation. Relying on a single, concentrated vapor retarder is not recommended. Generally, closed-cell foam insulations are used for these applications. Seams should be minimized. On multilayer systems, the seams should be staggered. Taped seams are only allowed as a complimentary closure system.

Supermarkets are one of the biggest and most noticeable applications for refrigeration systems. They face several issues, including changes in refrigerant, colder line temperatures, higher temperature hot gas defrost cycles, changing store designs, and pressures to reduce installation time to decrease store build time. In [2] are detailed many of the issues related to this market segment.

Using preinsulated pipe hangers is a concept that is gaining acceptance in supermarkets because it saves time and improves reliability by reducing condensation at hanger locations. The majority of piping on a supermarket is indoors, but for the outdoor and rooftop sections, the use of flexible jacketing-polyvinyl chloride (PVC), AL laminates, etc., is being evaluated, either installed at the job site or factory applied to improve the longevity and appearance of the job. Use of protective coatings that need periodic maintenance is becoming less specified.

Refrigeration piping on most supermarkets is found inside, but some stores are designed with 90% of the piping on the roof. Some elastomeric insulation products are being promoted as ultraviolet (UV) resistant and acceptable for use outdoors without the additional protection of coatings, jackets, or cladding materials. But UV protection is not the only issue when it comes to outdoor applications. Mechanical abuse (by birds, cats, people, etc.) and environmental abuse (by hail, sand, dirt, wind, rain, etc.) play a role in the reliability and longevity of the insulation system. For optimum performance, coatings, jacketing, or cladding should be used for outdoor applications.

The insulation system installed on a supermarket refrigeration system must be highly reliable, as it will operate 24 hours a day for up to 10 years. Closed-cell elastomeric materials have been used in this application for many years because they are extremely reliable and cost-effective. It is a primary product used for supermarket refrigeration applications because of its low WVT, allowable use temperature range, and ease of installation.

Using a coating or flexible jacketing can improve the appearance, durability, weather resistance, and longevity of the insulation on a unit. Flexible, closed-cell elastomeric insulation is the predominate product used in this application. A 2.0 cm thickness is commonly used.

Food processing, freezing, storage, and distribution applications often use ammonia refrigeration because of its lower operating costs.

As ammonia systems are designed for smaller applications at an economical up-front cost, they are getting more consideration than more expensive operating systems. While most areas do not exceed high temperatures above 70 °C, some sections may cycle from –40 °C to 120 °C. Lower temperatures (down to –20 °C) mean greater insulation thickness (5–8 cm) is usually required to prevent condensation. Typically, 8 cm of insulation is used to prevent condensation, as many of these applications are in high-humidity areas. The majority of the insulation is installed outdoors, so jacketing selection is critical. As a result of the cost and thickness required, polystyrene and polyisocyurante with a stainless steel jacket are the most common materials used. Of key concern is corrosion of iron pipe. Proper insulation installation (with no open or through seams) is a major concern, and use of secondary vapor-retarder systems is the norm.

The refrigeration market covers a broad spectrum of applications, each with unique requirements but all with a common goal: prevention of moisture intrusion and condensation to maintain long-term system reliability. Installation techniques are just as critical as material selection. The consequences of system failure can include degraded thermal performance of the insulation, higher system operating cost, inadequate cooling capacity, mold and mildew, ice formation, ruined ceilings, slippery floors, equipment downtime, and corroded pipes.

In below-ambient systems like refrigeration applications (including chilled water and cryogenic systems) closed-cell insulation products are preferred because of their low WVT and inherent moisture resistance. It's important to select the right insulation product for the application. Customer expectations must be matched to product performance and cost. Refrigeration applications are demanding and require careful consideration in material selection and installation to obtain optimum performance for the end user.

III. Optimization Model

The optimization method minimizes the analytical expression of various simple or compound optimization criteria. The computational model involves some known data as: general data, energy-economic parameters, referring data to rooms or piping and to construction elements or refrigerant utilized in refrigeration system.

In Figures 1 and 2 are presented calculation schema of refrigeration insulation for a flat and respectively cylindrical surface.

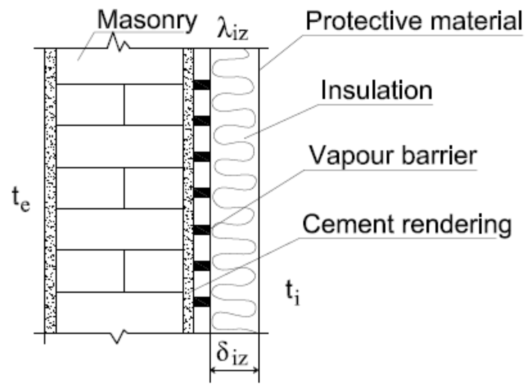

Fig. 1 Diagram of refrigeration insulation to a flat surface

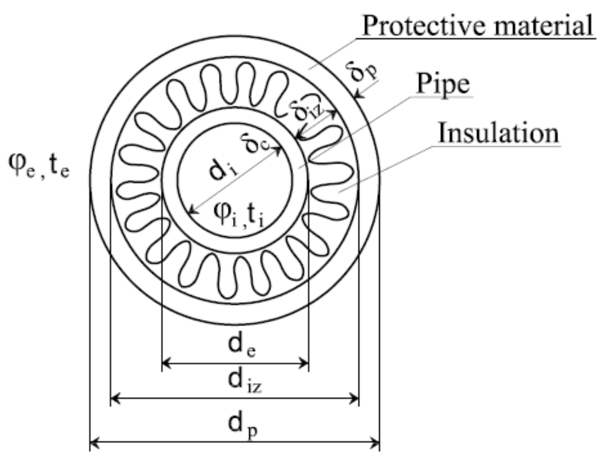

Fig. 2 Diagram of refrigeration insulation to a cylindrical surface

The thermal conductivity λ_{iz} of insulation is expressed as an analytical dependence:

$$\lambda_{iz} = b_0 + bt_m \quad (1)$$

in which b_0, b are constants depending on insulation material [11]; t_m – mean temperature of insulator layer.

Total resistance to heat transfer R is calculated with equations:

– for flat surfaces of cooled rooms:

$$R = \frac{\delta_{iz}}{\lambda_{iz}} + \left(\frac{1}{\alpha_i} + \sum_{j=1}^{NS} \frac{\delta_j}{\lambda_j} + \frac{1}{\alpha_e} \right) \quad (2)$$

– for cylindrical surfaces of cold pipes:

$$R = \frac{1}{\pi \alpha_i d_i} + \frac{1}{\pi \alpha_e d_p} + \frac{1}{2\pi} \left(\frac{1}{\lambda_c} \ln \frac{d_e}{d_i} + \frac{1}{\lambda_{iz}} \ln \frac{d_{iz}}{d_e} + \frac{1}{\lambda_p} \frac{d_p}{d_{iz}} \right) \quad (3)$$

where:

$$d_e = d_i + 2\delta_c;\ d_{iz} = d_e + 2\delta_{iz};\ d_p = d_{iz} + 2\delta_p \quad (4)$$

in which: δ_{iz} is insulation thickness; δ_j, λ_j – thickness and thermal conductivity of layer j of component material of a flat surface; δ_c –wall thickness of a pipe; δ_p – protective layer thickness of pipe insulation; d_i, d_e – inside and outside diameter of the pipe; α_i, α_e – internal and external heat transfer coefficients of component element of cooled environment; NS – material layers number of a element.

Analytic optimization criteria are minimized and is fulfilled the condition of air condensation prevent on insulation surface:

– flat surfaces:

$$\frac{t_e - t_i}{R} = \alpha_i (t_p - t_i) \quad (5)$$

– cylindrical surfaces:

$$\frac{d_{iz}}{d_e} \ln \frac{d_{iz}}{d_e} \geq \frac{2\lambda_{iz}}{\alpha_e d_e} \left(\frac{t_e - t_i}{t_e - t_{pr}} - 1 \right) \quad (6)$$

in which: t_i is cooled environment temperature (indoor air or refrigerant from pipe); t_e – outdoor air temperature; t_p – internal surface temperature of a flat wall; t_{pr} – air dew-point temperature.

It is assumed that the refrigeration system is one with vapour mechanical compression and electric drive.

The optimal insulation thickness can be determined by considering as optimization criteria: the insulation achievement cost, the operating costs, the energy embedded in insulation or the energy consumed to maintain low temperature [14].

A. *Economic Criterion*

Economic criterion adopted for optimizing refrigeration insulation thickness is the minimum updated total cost (capital cost and energy cost). Taking into account the specific investment cost for insulation I_{iz}, the annual cost for maintenance and repair of insulation C_{ir}, the annual cost of energy losses by insulated surface C_f and the expression of updated rate r for annual costs during normal recovery time:

$$r = \sum_{t=1}^{T} \frac{1}{(1+r_0)^t} = \frac{(1+r_0)^T - 1}{r_0 (1+r_0)^T}, \quad (7)$$

this criterion implies the minimizing of following objective function:

$$F_C = I_{iz} + \sum_{t=1}^{T} \frac{C_{ir} + C_f}{(1+r_0)^t} \quad (8)$$

in which r_0=1/T is depreciation rate for recovery period T (10–15 years).

The optimal insulation thickness is obtained by solving the equation: $\partial F_C / \partial \delta_{iz} = 0$. For *flat surfaces* that finally lead to the relation:

$$\delta_{iz} = \sqrt{\frac{r \sigma \tau c_f (t_e - t_i) \lambda_{iz}}{1000(rp+1) c_{iz}}} - \lambda_{iz} \left(\frac{1}{\alpha_i} + \sum_{j=1}^{NS} \frac{\delta_j}{\lambda_j} + \frac{1}{\alpha_e} \right) \quad (9)$$

For *cylindrical surfaces* is applied the method of successive approximations after explicating the objective function (8):

$$F_C = (rp+1)\,c_{iz}\delta_{iz}\left(d_e+\delta_{iz}\right)+\frac{r\sigma\tau c_f\left(t_e-t_i\right)}{1000\,R} \qquad (10)$$

in which: c_{iz} is the specific investment cost of a m^3 of insulation; p – the depreciation, repairs and maintenance rate for an insulation (0.04–0.07); σ – additional cold loss coefficient through pipe fittings or due to non-steady state (1.05–1.3); τ – the number of hours needed to provide cool during a year (1500–8760 hours/year); c_f –cooling energy cost price

B. Energy Criterion

The energy optimal insulation thickness is determined minimizing the sum of energy embedded in insulation E_{iz} and operating energy E_e required to maintain low temperature in cooled environment. Energy criterion is expressed analytically by the function:

$$F_E = E_{iz} + E_e \qquad (11)$$

For *cylindrical surfaces* this function receives particular form:

$$F_E = e_{iz}\delta_{iz}\left(d_e+\delta_{iz}\right)+\frac{\sigma\tau T\left(t_e-t_i\right)}{1000\,R} \qquad (12)$$

and could be minimized applying successive approximations method.

Explicating the equation (11) for *flat surfaces* and introducing minimum condition ($\partial F_E/\partial\delta_{iz}=0$), after a series of algebraic transformations, is obtained the term energy optimum insulation thickness for cooled rooms:

$$\delta_{iz}=\sqrt{\frac{\left(t_c-t_0\right)\left(t_e-t_i\right)\sigma\tau T\lambda_{iz}}{1000\eta_e\eta_f e_{iz}\left(t_0+273\right)}}-\lambda_{iz}\left(\frac{1}{\alpha_i}+\sum_{j=1}^{NS}\frac{\delta_j}{\lambda_j}+\frac{1}{\alpha_e}\right) \qquad (13)$$

in which: e_{iz} is specific energy embedded in one m^3 of insulation; t_c, t_0 – the condensation and vaporization temperatures of the refrigerant; η_e – average efficiency of obtaining electricity from primary energy (0.2–0.4); η_f – efficiency of real refrigeration cycle versus referential reversed Carnot cycle (0.6–0.8).

C. Energy-Economical Criterion

Energy-economical optimization criterion considers the two above criteria combined. Thus reflects in a more objective way the weight of technical and energy aspects during life-cycle of the insulated construction or pipe.

So, if are illustrated curves $F_C=f(\delta_{iz})$ and $F_E=f(\delta_{iz})$ in two perpendicular planes (Fig. 3), there is absolutely optimal point M ($F_{C,\min}$ and $F_{E,\min}$). This point represented in a third plane formed by axes F_C and F_E is a fictional point, because, in general, is not in the existence field of functional relationship $F_E=f(F_C)$. It is looked for another point N so that MN distance is minimized. It is defined a complex criterion that includes the two above mentioned in the form of minimizing the Euclidean distance in the plane (F_C, F_E):

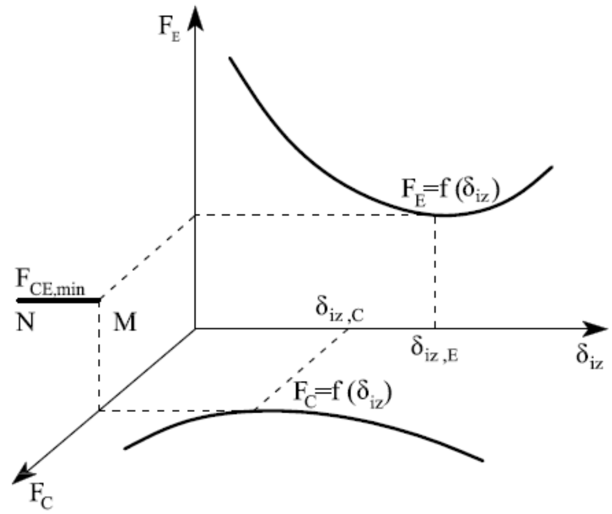

Fig. 3 3D-Representation of bicriterial optimization function

$$F_{CE}=\sqrt{\psi\left(F_C-F_{C,\min}\right)^2+(1-\psi)\left(F_E-F_{E,\min}\right)^2} \qquad (14)$$

where ψ is a criterial weight coefficient by which can be give preference to one or another of the component criteria in different prices circumstances, respectively in energy penury.

For *flat surfaces*, is obtained the general expression of optimum insulation thickness:

$$\delta_{iz}=\sqrt{\frac{\left[\psi rc_f+\frac{(1-\psi)T\left(t_c-t_0\right)}{\eta_e\eta_f\left(t_0+273\right)}\right]\frac{\left(t_e-t_i\right)\sigma\tau\lambda_{iz}}{1000}}{\psi(rp+1)c_{iz}+(1-\psi)e_{iz}}}-\lambda_{iz}\left(\frac{1}{\alpha_i}+\sum_{j=1}^{NS}\frac{\delta_j}{\lambda_j}+\frac{1}{\alpha_e}\right) \qquad (15)$$

By ψ = 1 and ψ = 0 in (14) or (15) are found particular cases of optimization on economic and energy criterion, expressed by relations (9) and (13) for flat surfaces and the relations (10) and (12) for cylindrical surfaces.

Based on the previously developed optimization model, two computer programs DEFRIZOP for cooled rooms and COFRIZOP for cold pipes have elaborated in FORTRAN programming language, for PC microsystems. These programs operate sequentially and have flow charts in Figures 4 and 5.

IV. Numerical Applications

It is exemplified the application of the proposed computational model for optimal sizing of insulation on a plastered external wall of a cooled room to t_i = −10 °C temperature, which operate all year round and on a steel pressure pipe carrying liquid ammonia at temperature t_i = −10 °C.

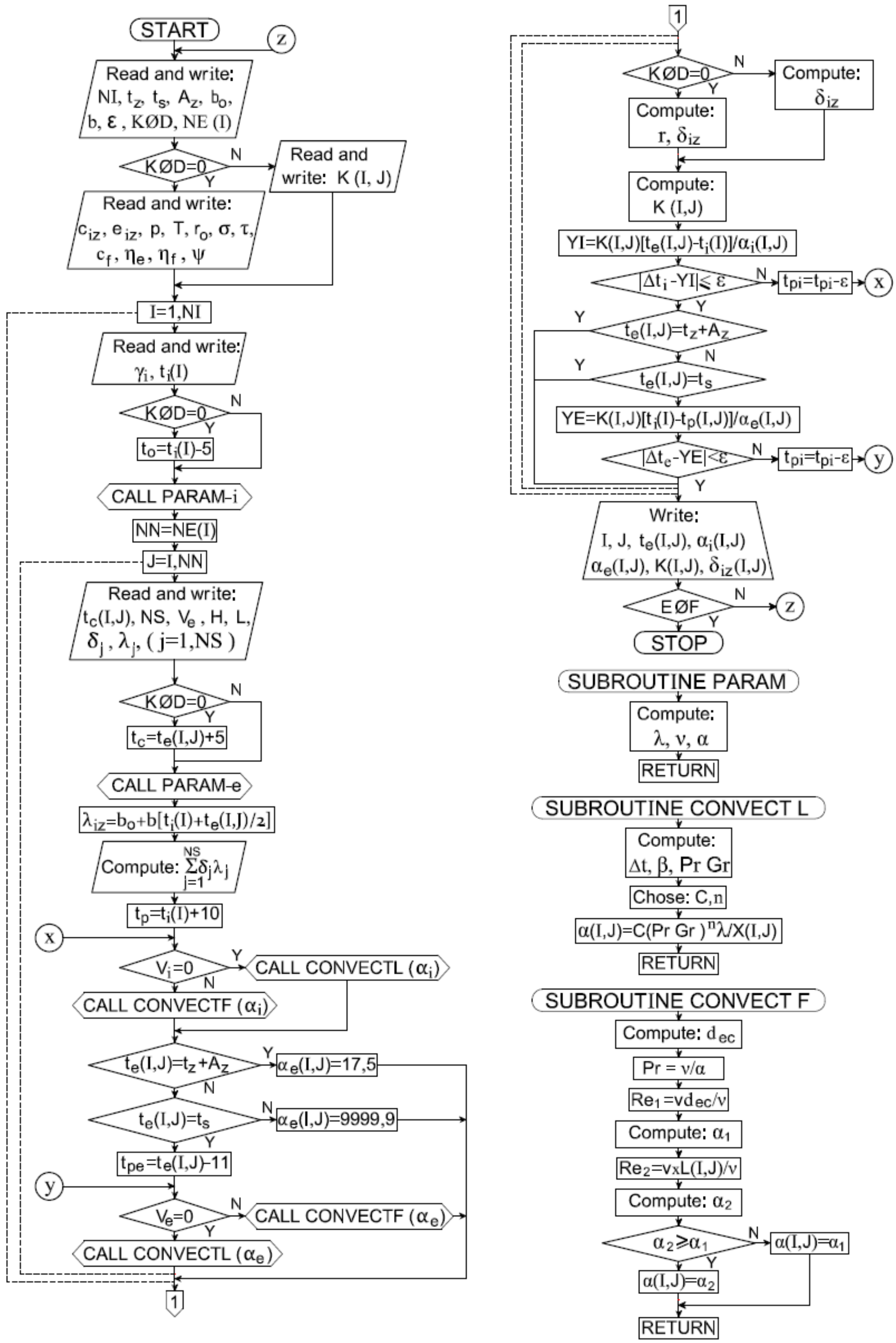

Fig. 4 Flow chart of DEFRIZOP program

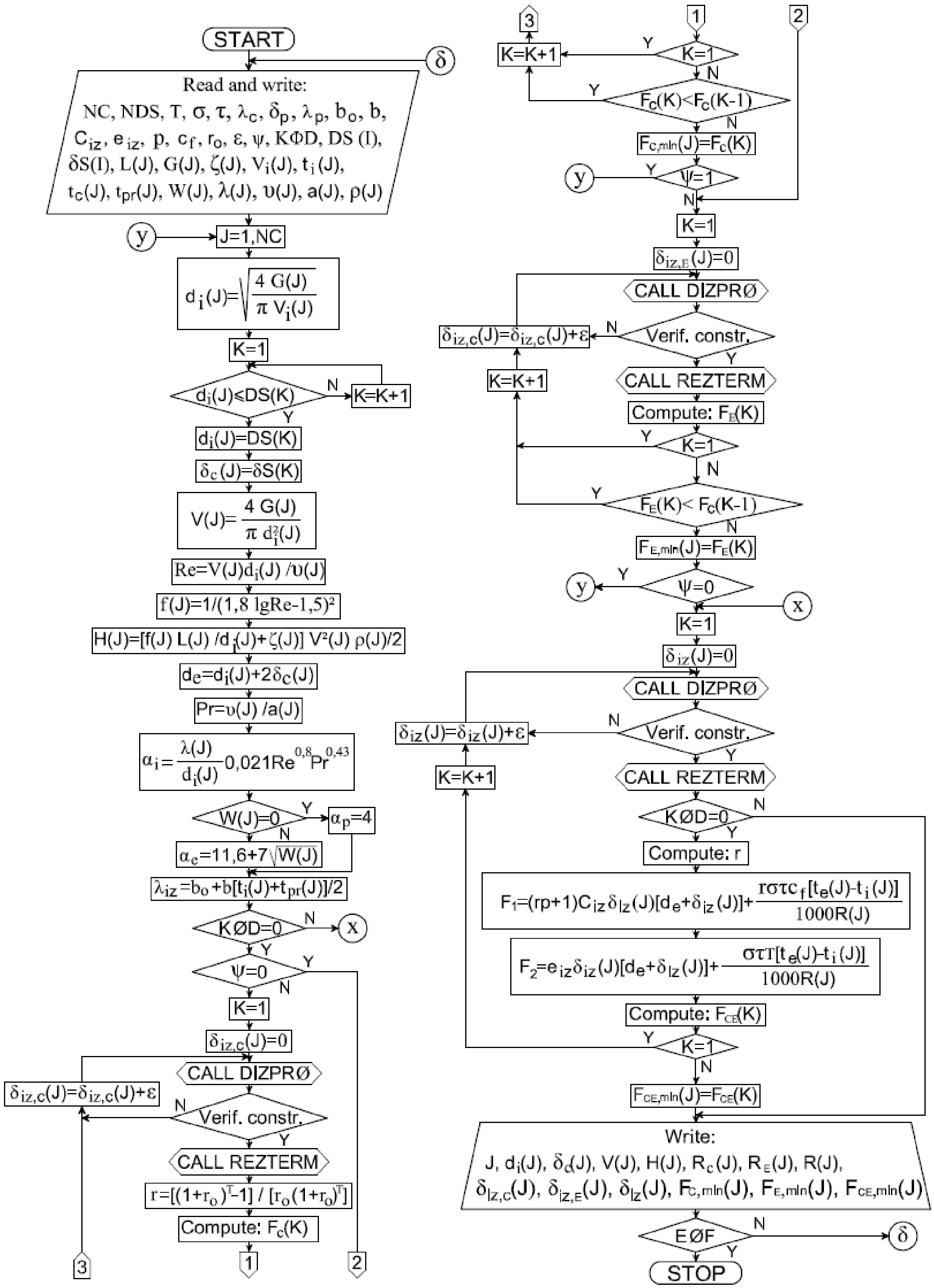

Fig. 5 Flow chart of COFRIZOP program

The external wall is north oriented, has dimensions 6×4 m, and are known general data: δ_1 = 0.02 m; λ_1 = 0.93 W/(m·K), δ_2 = 0.30 m, λ_2 = 0.80 W/(m·K), t_e = 30 °C, w_e = 4 m/s, w_i = 0 m/s, p = 0.05, T = 10 years, β_o = 0.1, σ = 1.1, η_e = 0.3, η_f = 0.6.

The cold pipe has diameters d_e/d_i = 219/203 mm, length L = 15 m, flow rate G = 0.0224 m^3/s and are known general data: t_e = 30 °C, w = 0 m/s, δ_p = 0.02 m, λ_p = 0.29 W/(m·K), p = 0.05, T = 10 years, σ = 1.1.

Using computer programs DEFRIZOP and COFRIZOP is performed a rating comparative study of these insulations both with optimization model and classical method. Consider several coefficients ψ and as insulation expanded polystyrene (EP) and mineral wool (MW). Are also allowed more values c_f to highlight their variation on insulation thickness. The numerical results obtained are summarized in Tables 1 and 2.

Table 1. Insulation thickness for external wall

c_f [€/kWh]	δ_{iz} [mm]											
	Classical method		Optimization model									
			Energy crit.		Energy-economical criterion c						Econ. crit.	
			ψ = 0		ψ = 0.25		ψ = 0.50		ψ = 0.75		ψ = 1.00	
	EP	MW	EP	MW	EP	MW	EP	MW	EP	MW	EP	MW
0	1	2	3	4	5	6	7	8	9	10	11	12
0.060	236	334	407	697	351	554	315	479	289	429	270	394
0.065					356	561	323	488	299	444	281	411
0.070					361	568	330	500	309	458	294	428
0.075					365	575	338	511	319	473	306	445

Table 2. Insulation thickness for refrigerant pipe

c_f [€/kWh]	δ_{iz} [mm]											
	Classical method		Optimization model									
			Energy crit.		Energy-economical criterion c						Econ. crit.	
			ψ = 0		ψ = 0.25		ψ = 0.50		ψ = 0.75		ψ = 1.00	
	EP	MW	EP	MW	EP	MW	EP	MW	EP	MW	EP	MW
0	1	2	3	4	5	6	7	8	9	10	11	12
0.015	100	120	360	435	265	335	250	315	315	295	165	220
0.016					265	335	250	310	320	300	170	225
0.018					270	340	290	320	320	300	175	235
0.020					270	345	295	230	325	310	185	245

V. Conclusions

From the performed study results the following:

– The insulation thickness determined based on economic criterion, and also especially energy criterion, is greater than the thickness usually practiced.

– Very high insulation thickness values obtained using exclusively energy optimization criterion, is due to the large weight of energy needed to maintain the low temperature in pipe compared with energy embedded.

– There is a slow variation of the optimal insulation thickness with the cooling energy cost.

– Applying complex optimization criterion for a higher weight of energy criterion and for equal weights of both component criteria, insulation thickness values are high; this situation is normalized admitting a decreased weight for energy criterion compared to the economic criterion.

The proposed optimization model is complex and more efficient. Developed computer programs are applicable to any significant changes in economic and energy policy. They can help achieve savings in capital and energy, particularly important in the current economic juncture.

References

[1] ASHRAE, *Fundamentals Handbook*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 2009.

[2] ASHRAE, *Refrigeration Handbook*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 2010.

[3] J.P. Curtis, Optimization of multiple thin thermal insulation layers, *Proceedings of the 3th IASME/ WSEAS Int. Conference on Heat Transfer, Thermal Engineering and Environment,* Corfu, Greece, August 20-22, 2005, pp. 424-429.

[4] N. Georgescu, Methodology to establish the total embedded energy in building materials, *Civil Engineering Journal*, Bucharest, no. 9, 1978.

[5] C.P. Hedlin, Moisture gains by foam plastic roof insulations under controlled temperature gradients, *Journal of Cellular Plastics*, no 3, 1977, pp. 313-316.

[6] V. Korsgaard, Innovative concept to prevent moisture formation and icing of cold pipe insulation, *ASHRAE Transactions*, vol. 99, no. 1, 1993, pp. 270-273.

[7] M.K. Kumaran, Vapour transport characteristics of mineral fibber insulation from heat flow meter measurements, In: ASTM STP 1039, *Water vapour transmission through building materials and systems: Mechanisms and measurement*, American Society for Testing and Materials, 1989, pp. 19-27.

[8] R.S. Lenox, P.A. Hough, Minimizing corrosion of cooper tubing used in refrigeration systems, *ASHRAE Journal*, vol. 37, 1995, pp. 11.

[9] J.F. Malloy, *Thermal insulation*, Van Nostrand Reinhold, New York, 1969.

[10] I. Sarbu, I. *Numerical modelling and optimizations in building services*, Polytechnic Publishing House, Timisoara, 2010 (in Romanian).

[11] I. Sarbu, *Refrigeration systems*, Mirton Publishing House, Timisoara, 1998 (in Romanian).

[12] I. Sarbu, C. Sebarchievici, Thermal rehabilitation of buildings, *NAUN International Journal of Energy*, vol.5, no.2, 2011, pp. 43-52.

[13] I. Sarbu, I. C. Sebarchievici, Effects analysis of additional thermal protection for retrofitted buildings, *Journal of Engineering and Applied Sciences*, vol. 6, no. 6, 2011, pp. 31-42.

[14] I. Sarbu, E. Valea, G. Ostafe, Insulation rating optimization for refrigerating systems, In: Recent Advances in Environmental Science, *Proceedings of the 9th WSEAS Int. Conference on Energy, Environment, Ecosystems and Sustainable Development*, Lemesos, Cyprus, March 21-23, 2013, pp. 110-114.

[15] M. Storkmann, Insulating against the low temperatures by flexible insulation materials, *Technical Building Equipments*, vol. 22, no. 5, Tg. Mures, Romania, 2004, pp. 60-62.

[16] W.C. Turner, J.F. Malloy, *Thermal insulation handbook*, McGraw Hill Book Company, New York, 1981.