Insulation rating optimization for refrigerating systems

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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 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.

Key-Words: Cooled rooms, Refrigerant piping, Insulation rating, Optimization model, Comparative analysis

1 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 insulation 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 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.

2 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.

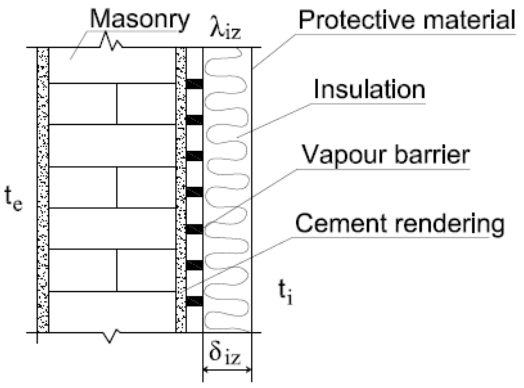

Fig. 1 Calculation scheme of refrigeration insulation to a flat surface

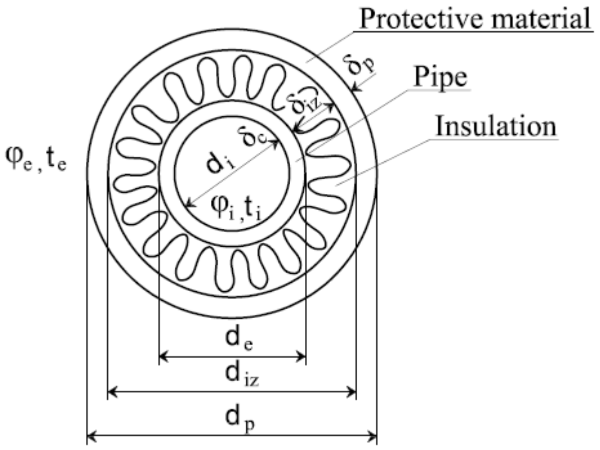

Fig. 2 Calculation scheme of refrigeration insulation to a cylindrical surface

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

$$\lambda_{iz} = b_0 + bt_m \tag{1}$$

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:

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

– for cylindrical surfaces of cold pipes:

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

where:

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

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:

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

– cylindrical surfaces:

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

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.

2.1 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:

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

this criterion implies the minimizing of following objective function:

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

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 expliciting the objective function (8):

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

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

2.2 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:

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

For *cylindrical surfaces* this function receives particular form:

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

and could be minimized applying successive approximations method.

Expliciting 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:

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

in which: e_{iz} is specific energy embeded 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).

2.3 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):

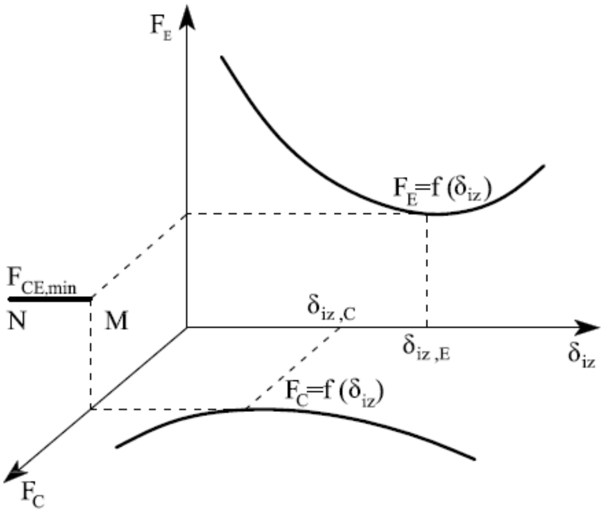

Fig. 3 3D Representation of bicriterial optimization function

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

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:

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

By $\psi = 1$ and $\psi = 0$ 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.

3 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.

The external wall is north oriented, has dimensions 6×4 m, and are known general data: $\delta_1 = 0.02$ m; $\lambda_1 = 0.93$ W/(m·K), $\delta_2 = 0.30$ m, $\lambda_2 = 0.80$ W/(m·K), $t_e = 30$ °C, $w_e = 4$ m/s, $w_i = 0$ m/s, $p = 0.05$, $T = 10$ years, $\beta_o = 0.1$, $\sigma = 1.1$, $\eta_e = 0.3$, $\eta_f = 0.6$.

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, $\delta_p = 0.02$ m, $\lambda_p = 0.29$ W/(m·K), $p = 0.05$, $T = 10$ years, $\sigma = 1.1$.

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 polystyrene (PE) 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.	
			$\psi = 0$		$\psi = 0.25$		$\psi = 0.50$		$\psi = 0.75$		$\psi = 1.00$	
	PE	MW	PE	MW	PE	MW	PE	MW	PE	MW	PE	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.	
			$\psi = 0$		$\psi = 0.25$		$\psi = 0.50$		$\psi = 0.75$		$\psi = 1.00$	
	PE	MW	PE	MW	PE	MW	PE	MW	PE	MW	PE	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

4 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.

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