ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

ENERGY EFFICIENCY OF NANOTECHNOLOGY COATINGS APPLIED TO REFLEXIVE INSULTAION

Marcela Álvares Maciel
Federal University of Fronteira Sul. Av. Dom João Hoffmann, 313. Erechim, Brazil.
marcela.maciel@uffs.edu.br

Marcus Antônio Viana Duarte
Federal University of Uberlândia. Av. João Naves de Ávila, 2121. Uberlândia, Brazil.
mvduarte@mecanica.ufu.br

Frederico Romagnoli Silveira Lima
Federal Center of Techonological Education of Minas Gerais. Av. Amazonas, 7675. Belo Horizonte, Brazil.
fredrsl@des.cefetmg.br

Abstract. *Strategies for Strategies for energy efficiency in industrial applications involve interfaces for maintainability, energy economy and environmental sustainability. Traditionally, thermal insulation is the most practical mechanism for steam pipe's energy efficiency. However, life cycle analysis presented thermal insulation residues as a still unsolved problem. So, many vegetal fibers as thermal insulation are proposal, while reflexive insulation researches are underdeveloped, especially for industrial applications. On the other hand, thermal coatings nanotechnology has been successfully developed as an alternative for conventional insulation. Before this context, energy efficiency of reflexive systems with thermal coatings as steam pipe's thermal insulation is investigated. Reflexive insulation provides thermal radiation heat transfer reduction through low emissivity and high reflectivity materials associates with air cavities. Factorial design methods are used for investigated factors principal effects and its interactions within heat transfer process in reflexive systems associate with thin films with ceramic micro-spheres or hollow glass particles. The results suggest reflexive insulation as a promising alternative technology, with considerable application particularities for each nanotechnology coatings*

Keywords: *Energy Efficiency , Reflexive Insulation, Factorial Design, Nanotechnology, Thermal Coatings*

1. INTRODUCTION

Given the current global energy crisis and increased environmental awareness, thermal efficiency in industrial environments is not only an economic concern but is an environmental concern, as well. Using insulation is one of the most practical strategies for increasing the energy efficiency of industrial piping, as insulation reduces the inevitable heat losses that arise due to differences between the process fluid temperature and room temperature. A technological alternative to thermal isolation is reflective insulation, which reduces radiative heat transfer using materials with low emissivity and high reflectivity; few studies have examined this alternative. However, the use of reflective insulation is still limited to the sub-roofs of buildings. (Winiarski and O'Neal, 1996; Medina, 2000; Soudbhan *et al.* 2005; Al-Homoud, 2005; Medina, 2006)

Recent developments of nanotechnology in the thermal insulator market, specifically special paints, could potentially be used in a reflective insulation system for saturated steam tubes. This combination could provide a solution for insulation systems over a wide range of operating temperatures, and the insulation thickness could be reduced from the thicknesses required by conventional insulation systems. To construct a reflective insulation system, at least one air cavity between the tubing and the insulating system is required. This air cavity also prevents corrosion under the insulation (corrosion is a typical problem with conventional resistive insulation). The general objective of this study was to evaluate the energy efficiency of reflective systems in saturated steam tubes. More specifically, the objective of this study was to evaluate the potential for using thin films based on nanotechnology (ceramic micro-spheres and hollow glass particles) in a reflective insulation system.

2. METHODOLOGY

2.1 Numerical modeling

Independent of the configuration of the insulation system, the temperature gradients in the axial and tangential directions are considerably smaller than the gradient in the radial direction. To simplify the mathematical modeling of this system, the insulation is treated as a one-dimensional system that is sufficiently long that edge effects can be neglected. The insulation was assumed to be a gray body when evaluating radiation exchanges, meaning that the surfaces are opaque and isothermal and emit and reflect diffusely; uniform radiosity and irradiation were also assumed.

ISSN 2176-5480

Thermal bridges (fasteners, construction accessories) were not included in the models, and perfect contact between the multiple layers of the insulating system was assumed. During operation, the temperature of the fluid in the mathematical models remained constant over a unit length of pipe. Daily or seasonal variations in room temperature or in the heating of the insulation system by solar radiation were not considered. Therefore, a permanent regime without heat-generating sources was characterized. The insulation system is subject only to natural convection conditions and is not exposed to wind.

This work consisted of mathematically modeling unidirectional heat transfer in a permanent regime for two different configurations of reflective insulation: a simple radiant barrier (SRB) and a double radiant barrier (DRB). The mathematical models available in the heat transfer literature were implemented using *Engineering Equation Solver©* to simulate the energy efficiency of reflective insulation systems. The levels of thermal resistance associated with radiative and convective heat losses in reflective insulating systems with a simple radiant barrier are schematically presented in Fig. 1 and mathematically described by Eq. (1) through Eq. (4), as in Incropera and Dewitt (2003).

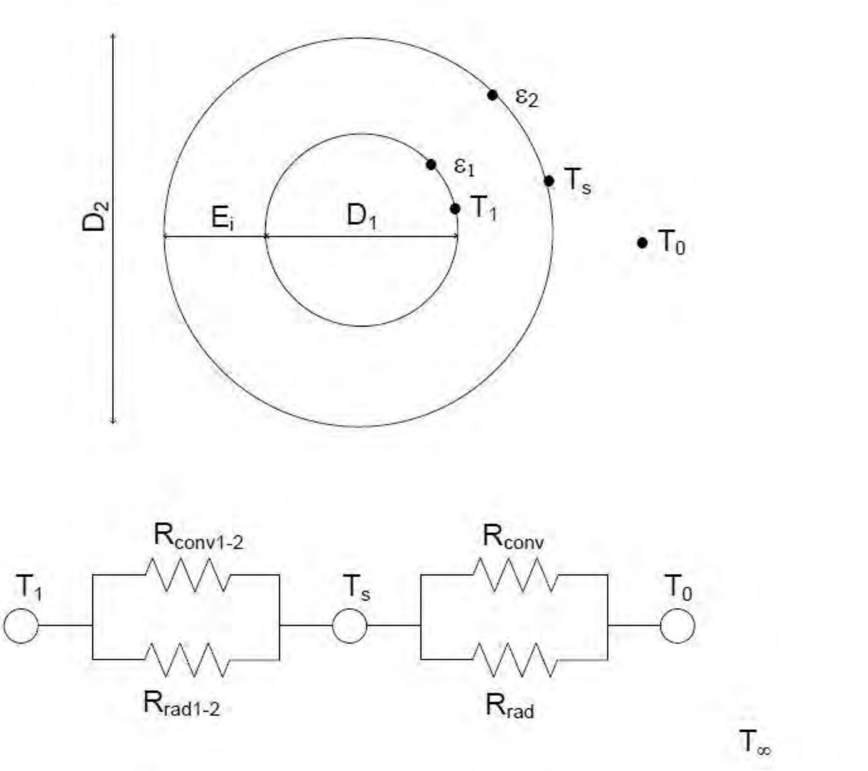

Figure 1. Design of the physical system and the thermal circuit describing the simple reflective insulation configuration.

$$R_{rad1-2} = \left[\pi D_2^2 \sigma (T_1 - T_s)(T_1^2 - T_s^2)\right]\left[\frac{1}{\varepsilon_1} + \frac{D_2^2}{D_1^2}.\left(\frac{1-\varepsilon_2}{\varepsilon_2}\right)\right] \quad (1)$$

$$R_{conv1-2} = \frac{\ln\left(\frac{D_2}{D_1}\right)}{2}\pi k_{ef} \quad (2)$$

$$R_{rad} = \frac{1}{\varepsilon_2.\sigma.(T_s - T_0).(T_s^2 - T_0^2)} \quad (3)$$

$$R_{conv} = \frac{1}{h_c} \quad (4)$$

Reflective insulation systems with a double radiant barrier are illustrated in Fig. 2, and the additional thermal resistances are described by Eq. (5) and Eq. (6). The mathematical expressions for the remaining resistances are similar to those described by Eq. (3) and Eq. (4).

$$R_{rad2-3}=\left[\pi.D_3^2.\sigma.(T_2-T_s).(T_2^2-T_s^2)\right]\left[\frac{1}{\varepsilon_2}+\frac{D_3^2}{D_2^2}.\left(\frac{1-\varepsilon_3}{\varepsilon_3}\right)\right] \quad (5)$$

$$R_{conv2-3}=\frac{\ln\left(\frac{D_3}{D_2}\right)}{2}\pi k_{ef} \quad (6)$$

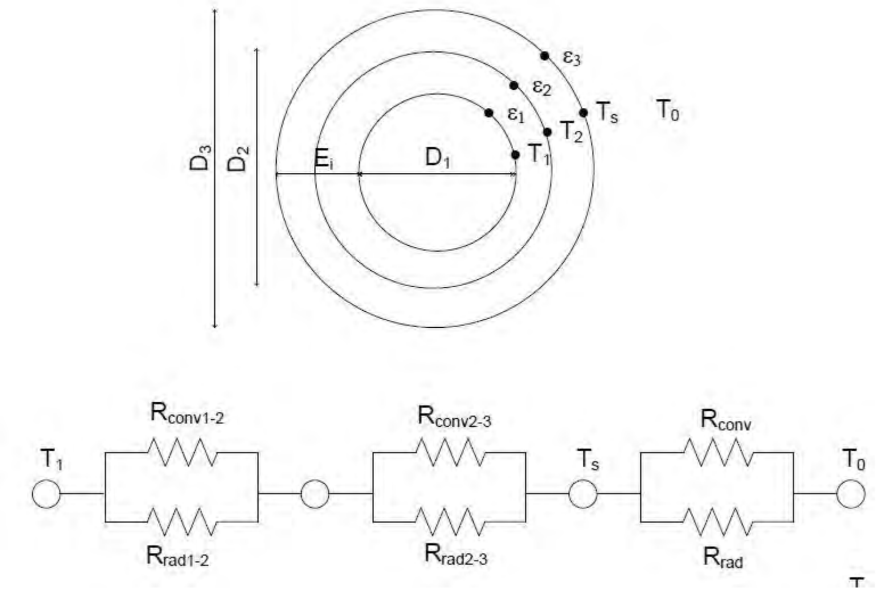

Figure 2. Design of the physical system and the thermal circuit describing the double reflective insulation configuration.

Equation (7) and Eq. (9) can be used to determine the effective thermal conductivity (k_{ef}).

$$\frac{k_{ef}}{k}=0{,}386\left(\frac{\Pr}{0{,}861+\Pr}\right)^{1/4}(Ra_c)^{1/4} \quad (7)$$

$$Ra_c=\frac{2.\left[\ln\frac{D_2}{D_1}\right]^4}{(D_2-D_1)(D_1^{-3/5}+D_2^{-3/5})^5}Ra_L \quad (8)$$

$$Ra_L=\frac{g\beta.(T_1-T_2)\left(\frac{D_2-D_1}{2}\right)^3}{\nu\alpha} \quad (9)$$

Equation (10) and Eq. (11) can be used to determine the convective heat transfer coefficient (h_c).

$$Nu_D=\frac{h_c D}{k} \quad (10)$$

$$Nu_D=\left\{0{,}60+\frac{0{,}387Ra_D^{1/6}}{\left[1+\left(\frac{0{,}559}{\Pr}\right)^{9/16}\right]^{8/27}}\right\}^2 \quad (11)$$

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The efficiency of the insulation system is given by Eq. (12), where q_s is the total heat loss without insulation, and q_c is the total heat loss with insulation.

$$\eta = 100\left(\frac{q_s - q_c}{q_s}\right) \tag{12}$$

2.2 Statistical modeling

A pilot experiment was performed to validate the numerical model. In this validation case, a test bench consisting of stainless steel tubes with diameters of 0.1 m and lengths of 1.0 m was simulated. The tubes were heated internally by two electrical resistors that provided maximum powers of 2500 W at 220V. The resistors were turned on and off using a control panel, and a PID controller was used for temperature adjustments. Eight T-type thermocouples were used to monitor the thermal profile of the prototypes. Four thermocouples were arranged radially within the tube, and the others were located concentrically within the insulation system. The temperature profiles were monitored for a 30-minute period at a sampling rate of five seconds after the system reached a steady state.

Saturated steam pipes were tested in the primary experiments. The thermal profiles of the prototype reflective insulation systems with an SRB or a DRB were maintained at operating temperatures (T_1) of 473 K (150 °C), 573 K (250 °C), and 673 K (350 °C). Three repetitions of each case were performed for a total of 18 experiments, which were also performed in a completely random order. A paired t-test with a 99% confidence interval was used to compare the results of the numerical and experimental studies.

Table 1 shows a compilation of the factors and levels involved in the heat transfer process in the reflective insulation materials. A two-level factorial design was adopted to study the efficiency of reflective insulation in extreme conditions. However, this method cannot quantify the nonlinearities that exist in the heat transfer process because of radiation, which must be accounted for. The nonlinearities inherent in reflective systems due to the presence of radiant barriers were evaluated in a subsequent experiment, shown in Tab. 9.

Table 1. Experimental factors and levels in the 2^8 factorial design

Factor	Level	
	(-)	(+)
A = Emissivity of the radiant barrier	0.1	0.9
B = Thickness of the air layer, m	0.005	0.025
C = Operation temperature, K	423	623
D = Emissivity of the tube	0.1	0.9
E = Emissivity of the insulation	0.1	0.9
F = Tube diameter, m	0.1	1
G = Room temperature, K	293	303
H = Number of radiant barriers	1	2

The number of radiant barriers was selected according to Maciel *et al.* (2009), which indicated that using multiple radiant barriers is only justified when the ratio of the thickness to the thermal conductivity is small. Therefore, the number of radiant barriers was limited to two for the high level and one for the low level. The two thickness levels of the air layer factor were selected based on Maciel *et al.* (2009), in which the high air layer thickness level was equivalent to that used in conventional insulation (0.025 m), and the low level was set to the minimum thickness permitted by construction methods (0.005 m). Values of 0.1 and 0.9 were selected for the superficial emissivity levels based on the studies found in Medina (2000). The operation temperature levels were determined as Maciel *et al.* (2009), and are set to the temperature limits of saturated steam. The levels for the room temperature factor were defined according to Medina (2000), which characterized the efficiency of insulation under different climatic conditions in Brazil.

A least-squared estimator was used to solve matrix b for the main effects and the second-order interactions among the factors of the 2^8 factorial design. This estimator is described by Eq. (13) in which X is the sensitivity matrix formed by the factor levels, and the first column is unity. Matrix Y consists of the responses of the tests. The analysis of variance technique was used to compare the different treatments. The ratio of the quadratic means of the treatments to that of the errors should be greater than the Fischer's statistic for a given number of degrees of freedom in the numerator and denominator at a 99% confidence interval.

$$[b] = 2\left\{[X]^T[X]\right\}^{-1}[X]^T[Y] = [b_0, b_1, ..b_k] \tag{13}$$

ISSN 2176-5480

3. RESULTS AND DISCUSSION

3.1 Validation of the numerical model

Table 2 presents the results of the paired t-test used to validate the experimental apparatus. Mean differences of (0.5 ± 0.7)% were observed between the numerical and the experimental methods using a 99% confidence interval. In this case, comparing the values of t_0 and $t_{0,005.9}$ allowed the null hypothesis to be accepted. Therefore, it can be concluded with 99% confidence that the values found by the numerical and experimental methods are statistically equal, verifying the accuracy of the numerical model.

Table 2. Results of the paired t-test used to validate the numerical model

Method	N	Mean	Standard Deviation
Numerical	9	86.339	4.963
Experimental	9	86.873	8.178
D	9	0.533	1.078
Confidence interval (99%)	(-0.203, 1.269)		
t_0	2.898		
$t_{0.005,9}$	2.179		
p-value	0.977		

3.2 Selection of the factors and levels

The entire 2^8 factorial design was studied using the numerical model (total of 256 experiments). Because replication is impossible with the numerical method, only first- and second-order interactions were considered. Thus, it was possible to evaluate the experimental error. Figure 3 presents the results regarding the primary effects of the emissivity of the radiant barrier (A), the thickness of the air layer (B), the operation temperature (C), the emissivity of the tube (D), the emissivity of the insulation (E), the tube diameter (F), the room temperature (G), and the number of radiant barriers (H). Changing the levels of the tube emissivity (D), the tube diameter (F), and the number of radiant barriers (H) from (-) to (+) caused substantial increases in the energy efficiency. Increasing the emissivity of either the radiant barrier (A) or the external insulation (E) resulted in a significant reduction in the efficiency of the insulation system. Increasing the thickness of the air layer (B) reduced the efficiency of the insulation system. Changing the room temperature level (G) did not affect the energy efficiency of the reflective system. The efficiency of the reflective system slightly increased when the operation temperature (C) was raised to 623 K (350 °C) from 423 K (150 °C).

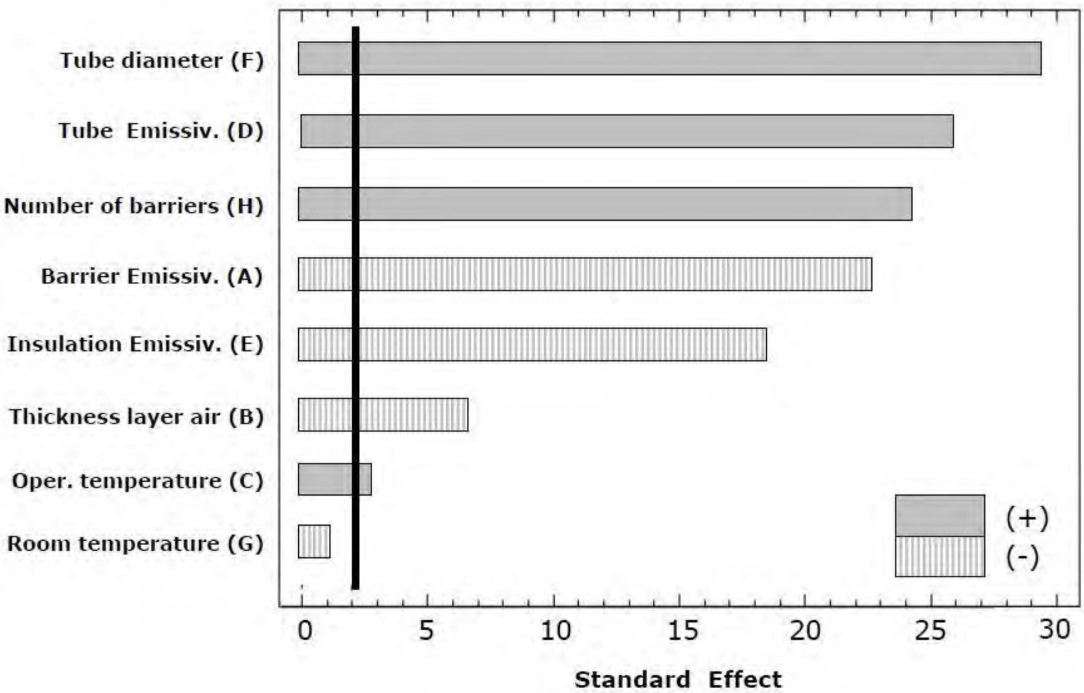

Figure 3. Hierarchy of the effects of the 2^8 factorial design.

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If increasing the level of a factor did not contribute positively to the result, which was the case for the external emissivity of the reflective system and the emissivity of the radiant barrier, then that factor was set at the low level to maximize the efficiency of the reflective system. Thus, it was determined that the surfaces must exhibit low emissivities. The definition of low emissivity (0.1) for the radiant barrier agrees with international guidelines. Using a small air layer thickness is interesting not only from the perspective of energy efficiency but also for economic reasons, as the reduced surface area requirements minimize material consumption. In general, the surface coating of the tubes naturally exhibits a high emissivity. Therefore, knowing that a higher tube emissivity increases the energy efficiency, the high level of this factor was selected. The operating temperature, the number of barriers, and the diameter of the tube remain to be determined in the experimental study. The tube diameter was not studied, due to the limitations of the experimental apparatus. However, it must be noted that experiments utilizing smaller-diameter pipes produces less dramatic results; the efficiency increases as the diameter increases.

3.3 Ceramic micro-spheres

As stated above, the following factors will be the experimental subjects in a complete factorial design: the operating temperature with levels of 423 K (150 °C) and 623 K (350 °C) and the number of radiant barriers (single or double). The insulation, which is the external portion of the reflective system, is a third factor. Thin films composed of ceramic micro-spheres were chosen for insulation. Thus, the potential of this material as insulation in reflective systems was evaluated using the effects of the radiant barriers themselves as a reference. Table 3 presents a compilation of the factors and levels selected for the 2^3 factorial design.

Table 3. Factors and levels of the 2^3 factorial design

Factor	Level	
	(-)	(+)
A = Number of radiant barriers	1	2
B = Thickness of the air layer, m	423	623
C = Insulation I (ceramic micro-spheres)	0	1

One complete factorial design was performed with three replications of each treatment (R1, R2, and R3) for a total of 24 experiments. Table 4 presents the results of these experiments. The order of the experiments and replications was randomized, and the numbers in parentheses that accompany the responses of the experiment in Tab. 4 indicate the sequence of tests. Based on these results, it is possible to estimate the effects of the operation temperature, the number of barriers, and the thermal insulation, as well as the interactions among them.

Table 4. Experimental results for the 2^3 factorial design

T	A	B	C	AB	BC	AC	ABC	Efficiency, %			
								R_1	R_2	R_3	Mean
1	(-)	(-)	(-)	(+)	(+)	(+)	(-)	80.3 (5)	84.7 (12)	83.0 (17)	82.7
A	(-)	(+)	(-)	(-)	(+)	(-)	(+)	86.6 (8)	85.5 (9)	86.1 (21)	86.1
B	(+)	(-)	(-)	(-)	(-)	(+)	(+)	87.0 (2)	89.2 (15)	87.3 (22)	87.8
Ab	(+)	(+)	(-)	(+)	(-)	(-)	(-)	90.7 (3)	90.2 (13)	90.4 (18)	90.5
C	(-)	(-)	(+)	(+)	(-)	(-)	(+)	71.7 (1)	74.3 (10)	71.8 (19)	72.6
Ac	(-)	(+)	(+)	(-)	(-)	(+)	(-)	81.0 (6)	81.1 (14)	81.1 (23)	81.1
Bc	(+)	(-)	(+)	(-)	(+)	(-)	(-)	88.6 (4)	88.0 (16)	87.4 (20)	88.0
abc	(+)	(+)	(+)	(+)	(+)	(+)	(+)	89.9 (7)	89.7 (11)	90.1 (24)	89.9

Table 5 presents a synthesis of the results of performing an analysis of variance on the experimental observations. A 99% confidence interval was employed; therefore, the statistically significant effects are those with F_0 values greater than the critical F value (8.5) and with p-values below 0.01. Table 6 shows that all of the effects were statistically significant at this level with the exception of the interaction between the operation temperature and the insulation (AC).

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Table 5. Analysis of variance of the final 2^3 factorial design

Source of variation	Sum of squares	Degrees of freedom	Quadratic means	F_0	*p-value*
A	101.764	1	101.764	87.45	0.0000
B	428.077	1	428.077	367.85	0.0000
C	89.707	1	89.707	77.09	0.0000
AB	20.350	1	20.350	17.49	0.0007
AC	6.977	1	6.977	6.00	0.0241
BC	81.107	1	81.107	69.70	0.0000
ABC	12.241	1	12.241	10.52	0.0048
Error	18.619	16	1.095		
Total	758.843	23		*F* critical = 8.5	

Table 6 presents the results of an estimation of the main effects and interactions, including the upper and lower limits of the confidence intervals. For a confidence interval of 99%, the number of radiant barriers is the primary contributor to the energy efficiency of the reflective insulation system, as using a double radiant barrier provides an improvement of (8.5 ± 0.6)% over the simple barrier. However, the magnitude of the interaction between the number of barriers and the insulation (BC) does not allow for the inherent effects of these factors to be evaluated in isolation. This interaction can be observed to increase the energy efficiency by just (3.7 ± 0.6)%. Increasing the operation temperature from 423 K (150°C) to 623 K (350 °C) increases the energy efficiency by (4.1 ± 0.6)%. Using the insulation reduced the energy efficiency of the reflective system by (3.9 ± 0.6)%. Therefore, the insulation system being evaluated is inefficient independently of the number of radiant barriers, and the use of radiant barriers alone (simple or double) produces the most satisfactory results in terms of energy efficiency.

Table 6. Estimated main effects and interactions

Effect	Estimation	99% Confidence Interval	
		Lower Limit	Upper Limit
Mean	84.839	84.524	85.154
A	4.118	3.489	4.706
B	8.447	7.859	9.076
C	- 3.867	- 4.455	- 3.237
BC	3.677	3.089	4.306

Increasing the operation temperature from 423 K (150 °C) to 623 K (350 °C) increased the efficiency of the insulation system, as the radiation resistance changes with the 5 temperature to the fourth power. It is important to stress that increasing the operation temperature does not increase the efficiency of a conventional insulation system. Higher performance of conventional insulation systems is associated with lower thermal conductivity, and the thermal conductivity tends to increase as the temperature increases, thereby reducing the insulation potential of the material.

The effect of increasing the number of barriers and using a double radiant barrier over a simple radiant barrier provided a much more substantial efficiency increase than increasing the operation temperature. These results were also predicted by the numerical method. As discussed above, the use of multiple radiant barriers in reflective insulation systems is only justified when the performance of the insulation is unsatisfactory.

The reduction of the energy efficiency of the reflective insulation system due to the inherent effect of the insulation was unexpected. Because the system was assumed to be an opaque body and a gray surface, a possible explanation for the reduced efficiency of the reflective system stems from a critical radius for the insulation. However, this explanation is refuted by the numerical method, which did not produce the effect observed in the experiment independent of the thickness of the insulation, which had a thermal conductivity of 0.1 W/mK. Thus, the comparison between the numerical and experimental results suggests that the insulation may not be characterized by its conductivity resistance alone. Recent research in the field of radiative heat transfer in materials involving nanotechnology, such as thin insulating films, have demonstrated that the results are extremely dependent on the spectral structure of the radiation, which may be reflected, absorbed, or transmitted, as shown in German and Grinchuk (2002) and Dombrovsky (2005). Therefore, these materials cannot be characterized as opaque bodies but must be treated as semi-transparent media.

These results show that the proposed numerical model, which assumes gray, opaque, and isothermal surfaces that diffusely emit and reflect and are characterized by uniform radiosity and irradiation, does not accurately reflect the heat transfer processes in thin films with ceramic microspheres. Therefore, we designed a new set of experiments to evaluate the behavior of this insulation.

ISSN 2176-5480

Determining the spectral components of the radiation from thin films is somewhat complex, as the radiation depends heavily on the optical properties of the substrate and the medium. In these cases, absorption and reflection may not be treated as surface phenomena and may be strongly influenced by the volumetric effects that occur in the interior of the insulation, as shown in Incropera and Dewitt (2003). Therefore, a 2^2 factorial design was prepared to evaluate possible explanations of the observed energy efficiency reduction by the reflective insulation. The work presented in Siegel and Howel (2003) was used as a reference for heat transfer in thin films. The levels of the insulation thickness factor were 0.001 m and 0.001 m, and the levels of the substrate reflectivity were 0.1 and 0.9, as shown in Tab. 7.

Table 7. Factors and levels of the 2^2 factorial design

Factor	Levels	
	(-)	(+)
A = Thickness of insulation I (ceramic micro-spheres)	0.001	0.003
B = Emissivity of the substrate	0.1	0.9

Table 8 presents the results of an analysis of variance treatment of the experimental observations. With three replications of each experiment, there were a total of 22 degrees of freedom, nine of which were used to estimate the experimental error. Statistical significance at the 99% confidence level is indicated by an F_0 value greater than the critical F value (10.5) and a p-value below 0.01. At this confidence level, only changing the substrate (B) had a statistically significant effect on the energy efficiency of the reflective system. Similar results were presented in German and Grinchuk (2002) in which applying composites containing ceramic micro-spheres in substrates with low emissivity was found to produce null or even detrimental effects, indicating that the presence of the micro-spheres increased the heat transfer of the insulated surface. It can thus be concluded that the efficiency of composites containing ceramic microspheres depends on whether high-emissivity substrates are used.

Table 8. Analysis of variance for the 2^2 factorial design

Source of variation	Sum of squares	Degrees of freedom	Quadratic means	F_0	*p-value*
A	23.852	1	23.852	8.5	0.03
B	102.422	1	102.422	36.5	0.0012
AB	9.861	1	9.861	2.8	0.1224
Error	25.255	9	2.806		
Total	161.389	12		Fcritical=10.5	

3.4 Hollow glass particles

Table 9 presents a compilation of the factors and levels of the factorial experimental design used to evaluate the efficiency of the reflective system with a thin film containing hollow glass particles. In this case, configurations were evaluated for reflective systems with a simple, double, or triple radiant barrier. The purpose of using a third radiant barrier was to investigate the possibility of a nonlinear response. The insulation factor was assigned qualitative levels of 0 and 1, which correspond to the absence and presence, respectively, of insulation containing hollow glass particles.

Table 9. Factors and levels of the mixed factorial design

Factor	Levels		
	(-1)	(0)	(+1)
A = Insulation II (hollow glass particles)	0	-	1
B = Number of radiante barriers	1	2	3

The energy efficiency results obtained for each of the three replications that were performed are presented in Tab. 10. Minimum efficiencies of 66% and maximum efficiencies of 92% were observed for the configurations of the reflective insulation with a simple barrier and with a triple barrier, respectively. Comparing the two configurations with a simple radiant barrier reveals that the presence of insulation reduced the efficiency of the reflective system. However, the presence of insulation increased the energy efficiency in the configurations with double or triple barriers .

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Table 10. Experimental results for the new factorial design

Tc	A	B	Efficiency, %			
			R_1	R_2	R_3	Mean
1	(-)	(-)	74.7 (4)	79.8 (10)	81.6 (14)	78.7
2	(-)	(0)	79.8 (3)	79.7 (12)	79.9 (13)	79.8
3	(-)	(+)	84.2 (5)	83.8 (11)	84.2 (18)	84.1
4	(+)	(-)	66.1 (6)	66.0 (8)	66.8 (15)	66.3
5	(+)	(0)	88.5 (2)	88.3 (7)	88.6 (16)	88.4
6	(+)	(+)	92.0 (1)	92.5 (9)	92.2 (17)	92.2

Table 11 presents the results of the analysis of variance treatment of the results in Tab. 10. Statistical significance at a 99% confidence level is indicated by an F_0 value greater than the critical F value (10.5) and a p-value below 0.01. The insulation was not a statistically relevant effect at the 99% confidence level. However, the interaction between the insulation and the number of barriers does not allow the effects of these factors to be evaluated separately, as the effect of the interaction between the number of barriers and the insulation (AB) is as significant as the effect of the number of barriers itself (B).

Table 11. Analysis of variance for the 2^2 factorial design

Source of variation	Squared sums	Degrees of freedom	Quadratic means	F_0	*p-value*
A	734.768	2	367.384	37.495	0.0000
B	9.827	1	9.827	1.003	0.394
AB	317.241	1	317.241	32.377	0.0004
Error	137.176	14	9.798		
Total	1262.43	17		Fcritical=10.5	

Figure 4 and Fig. 5 present the experimental results in terms of the inherent effects and the interactions among the factors, respectively. The inherent effect of the insulation (A) was less pronounced than was the effect of the number of barriers (B). However, the effect of the number of radiant barriers exhibited nonlinear behavior, suggesting that there is a limit to the increase in energy efficiency that is achievable using multiple radiant barriers. Even though the inherent effect of the insulation was essentially negligible, its interaction with the number of radiant barriers indicated interesting results in terms of the energy efficiency improvement, which was approximately 10%. This improvement is not observed in the configuration with simple radiant barriers. The efficiency of reflective systems using insulation is conditional on the use of double or triple radiant barriers. The reverse situation is obtained with simple radiant barriers in which including insulation reduced the efficiency by more than 10%.

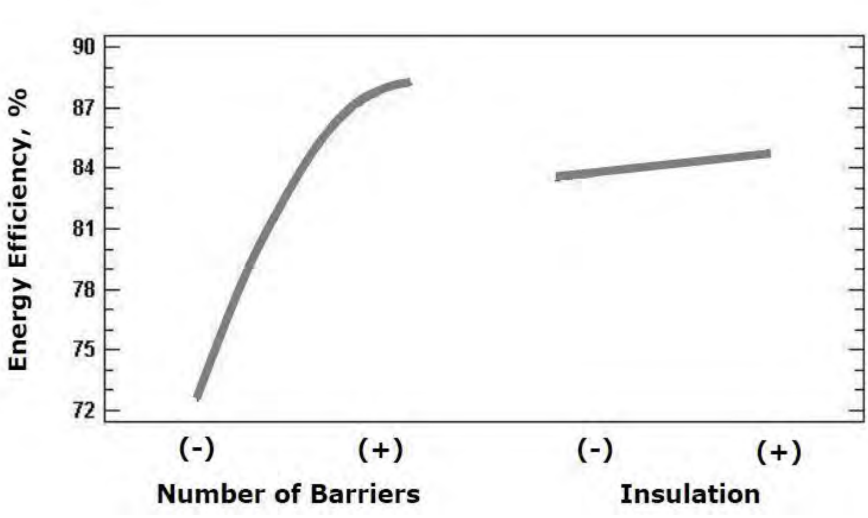

Figure 4. Inherent effects of insulation II and the number of radiant barriers.

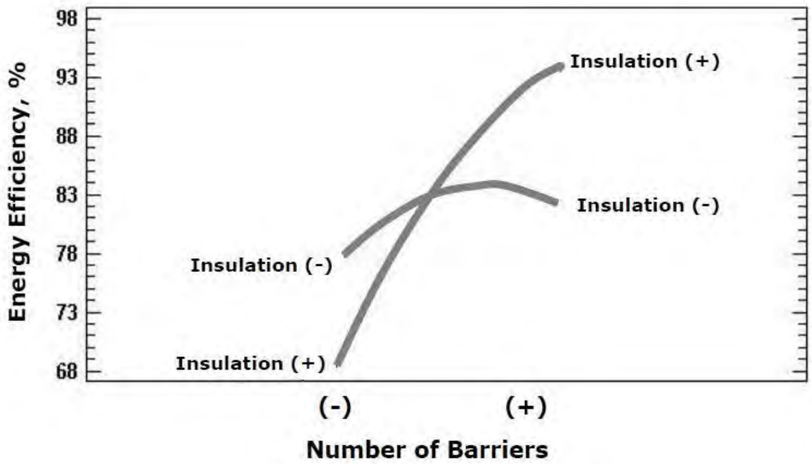

Figure 5. Effects of the interaction between insulation II and the number of radiant barriers.

Table 12 presents estimations of the inherent effects and the interactions, including the upper and lower limits of the confidence interval. With a 99% confidence interval, the number of radiant barriers is the main factor that contributes to the energy efficiency of the reflective insulation system, and a triple radiant barrier increases the efficiency by (16 ± 6)% over a system with a simple radiant barrier. The presence of the insulation increased the efficiency by (10 ± 6)% due to the interaction of this factor with the number of radiant barriers.

Table 12. Estimated main effects and interactions

Effectt	Estimation	99% Confidence Interval	
		Lower Limit	Upper Limit
Mean	84.133	79.655	88.610
A	15.650	9.318	21.982
B	1.477	-3.693	6.647
AB	10.283	3.953	16.613

3.5 Comparison between reflective insulation and traditional insulation

Comparing the energy efficiencies of traditional insulation systems using glass wool and the triple reflective system with hollow glass particles reveals that the two systems exhibit equivalent efficiencies on the order of 90% at an operation temperature of 423 K. The two systems also exhibited similar energy efficiencies at temperatures between 523 and 623 K with a maximum difference of 3%. Comparing the costs of traditional insulation systems using glass wool and the triple reflective system with hollow glass particles suggests that the cost of the reflective system is only competitive with that of the traditional system when the temperature of the operation system is between 523 and 623 K independently of the diameter of the tubing.

4. CONCLUSIONS

The use of reflective insulation, particularly as thermal insulation of pipes, is still largely unexplored in Brazil. Therefore, the energy efficiency of reflectively insulated steam pipes was studied in this article. Numerical modeling clarified how various factors involved in heat transfer in reflective insulation systems affect the energy efficiencies of these systems. Because a low radiant barrier emissivity was assumed in the characterization of the reflective insulation, the operation temperature and the number of barriers were found to be the main factors that can provide increased energy efficiency.

The lack of knowledge regarding the thermal-physical properties and heat transfer processes of insulation based on nanotechnology justifies the experiments that were performed. Comparing the numerical and experimental results confirmed that these products cannot be characterized simply by their conductivity resistances. Insulation with ceramic micro-spheres produced unsatisfactory energy efficiency results because the insulation was applied over an aluminum substrate, which increased the level of heat transfer. These results suggest that the insulation functions as a semi-transparent material when exposed to radiation and that volumetric phenomena in the medium play a role in heat transfer. Similar results are found in the literature and indicate that the low emissivity of the substrate is responsible for

ISSN 2176-5480

the increased heat transfer. Therefore, any applications of this product would be restricted to substrates with high emissivities.

In contrast, the insulation with hollow glass particles produced extremely satisfactory energy efficiencies when used in combination with triple radiant barriers. It must be stressed that this satisfactory energy performance is the result of the interaction between the insulation and the number of radiant barriers. In other words, using either the insulation or the radiant barriers by themselves would not reproduce the performance observed when both are employed. Therefore, we propose an alternate insulation system for temperatures of up to 623 K (350 °C). This system consists of three radiant barriers with a maximum emissivity of 0.1, separated by a 0.005-m air layer, and using 0.003 m thick insulation layers with hollow glass particles. It is important to stress that this configuration can be applied to horizontal pipes of any diameter without a loss in efficiency.

5. ACKNOWLEDGMENTS

We would like to thank the funding agencies, CAPES, CNPq, and FAPEMIG, as well as the CEFET-MG and KAEFER ISOBRASIL, for their financial support.

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7. RESPONSIBILITY NOTICE

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