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Thermal analysis in an air conditioning duct: An experimental design approach

Análise térmica em duto de ar condicionado: uma abordagem utilizando planejamento experimental

Análisis térmico en un conducto de aire acondicionado: un enfoque de diseño experimental

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Abstract

The main purpose of this work is to perform a thermal analysis in an air conditioning duct to verify the influence of the thermal properties of the insulating material on the minimum thermal insulation thickness necessary to avoid the condensation of water vapor present in the air. The mathematical formulation is based on Fourier's law and the first law of thermodynamics. A response surface, a contour plot and a mathematical model for the analyzed response variable, were obtained from an experimental design. Results indicate that the reduction of thermal conductivity and increase of emissivity of the insulating material contribute to the reduction of the minimum thermal insulation thickness.

Keywords: Air conditioning; Condensation; Duct-work; Thermal insulation.

Resumo

Este trabalho tem por objetivo realizar uma análise térmica em um duto de ar condicionado para verificar a influência das propriedades térmicas do material isolante na espessura mínima de isolamento térmico necessária para evitar o efeito da condensação do vapor d'água presente no ar. A formulação matemática é baseada na lei de Fourier e na primeira lei da termodinâmica. A partir do planejamento experimental, foram obtidos uma superfície de resposta, uma curva de contorno e um modelo matemático para a variável de resposta em análise. Resultados indicam que a redução da condutividade térmica e aumento da emissividade do material isolante contribuem para a redução da espessura mínima de isolamento térmico necessária para evitar o efeito da condensação.

Palavras-chave: Climatização; Condensação; Rede de dutos; Isolamento térmico.

Resumen

Este trabajo tiene como objetivo realizar un análisis térmico en un conducto de climatización para comprobar la influencia de las propiedades térmicas del material aislante sobre el espesor mínimo de aislamiento térmico necesario para evitar el efecto de condensación del vapor de agua presente en el aire. La formulación matemática se basa en la ley de Fourier y la primera ley de la termodinámica. Del diseño experimental se obtuvo una superficie de respuesta, una curva de contorno y un modelo matemático para la variable de respuesta analizada. Los resultados indican que la reducción de la conductividad térmica y el aumento de la emisividad del material aislante contribuyen a la reducción del espesor mínimo de aislamiento térmico necesario para evitar el efecto de condensación.

Palabras clave: Aire acondicionado; Condensación; Conductos; Aislamiento térmico.

1. Introduction

Indoor air quality is a global concern of the modern world. To provide air quality, it is important to have control of various parameters such as temperature, relative humidity, atmospheric pollutant concentrations and air changes per hour. Several studies indicate that air quality and thermal comfort significantly influence worker productivity, rates of respiratory disease, allergies, and asthma symptoms (Fisk & Rosenfeld, 1997; Huizenga et al., 2006; Lan et al., 2011)

In certain situations, where it is impossible to maintain acceptable comfort levels with natural ventilation alone, artificial climate control becomes essential for people to perform their activities optimally, in comfortable conditions and with a sense of well-being.

In central air-conditioning systems, air is cooled in the evaporator and conducted to the environments to be air conditioned through a structural assembly known as the ductwork. Such systems are commonly employed in the air conditioning of commercial buildings, malls, convention centers, large hotels, pharmaceutical industries, hospitals, etc.

Metal ducts used for air conditioning transport must be thermally insulated for two main reasons: reduce heat transfer from the outside environment to the interior of the duct and avoid condensation of water vapor in the air when in contact with the cold surface of the duct.

Research indicates that if the thickness of the thermal insulation is not sufficient to prevent the effect of condensation, fungal germination and proliferation will occur in the air conditioning ducts, compromising the air quality in the air-conditioned environment (Morey & Williams, 1991; Pasanen et al., 1993). Other factors that may affect the growth of microorganisms in duct networks are: high temperature levels, relative humidity and dust present in the air that is blown into the air-conditioned environment (Li et al., 2010).

Gomez et al. (2020) evaluated the influence of temperature and relative humidity of the outside air, and insufflation temperature (internal) on the minimum thickness of rock wool, coated with an aluminum film, required to avoid the effect of condensation in an air conditioning duct. The authors observed that an increase in the temperature and relative humidity of the external air and a reduction in the internal air temperature contribute to the increase in the minimum thickness of rock wool necessary to avoid condensation of water vapor present in the external air when in contact with the surface of the duct.

In this sense, the purpose of this work is to perform a thermal analysis in a rectangular duct for air conditioning transport, to quantify the influence of the thermal conductivity and the emissivity of the insulating material on the minimum thermal insulation thickness necessary to avoid the effect of condensation. It is a purely theoretical research with a predominantly quantitative analysis, which is based on works reported in the literature (Pereira et al., 2018; Gomez et al., 2020).

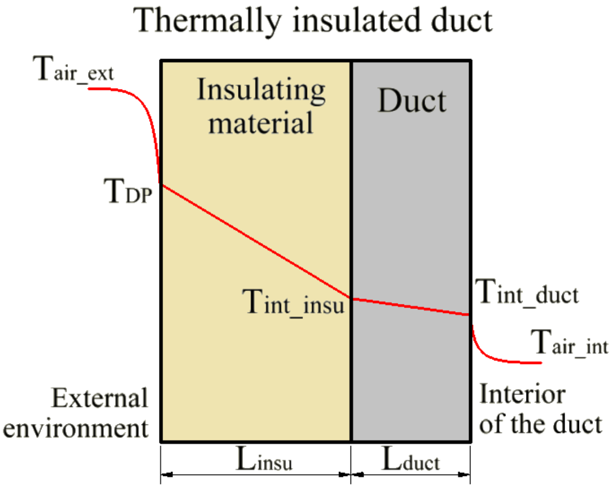
2. Methodology

For this analysis, consider Figure 1, which illustrates the temperature distribution in the cross section of a thermally insulated duct for air conditioning transport. It was considered a steady state, one-dimensional heat transfer from the external environment to the interior of the duct and no internal energy generation, making the temperature profiles along both the insulating material and in the duct to be linear.

Heat transfer occurs by convection and radiation on the external surface of the thermal insulation, by conduction on the insulating material and on the duct wall, and by convection on the internal surface of the duct, as illustrated in the equivalent thermal circuit (Figure 2).

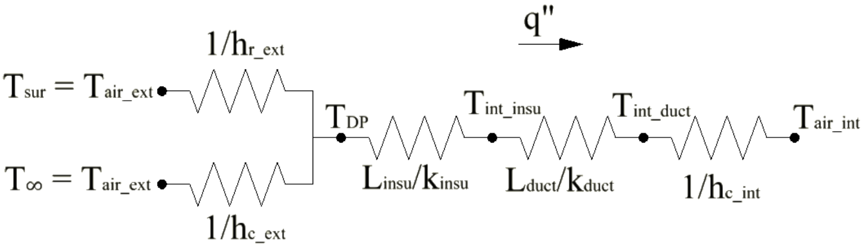
The minimum thermal insulation thickness required to prevent the effect of condensation (L_{insu}) is obtained considering that the temperature on the surface outside the thermal insulation, in contact with the external environment, is equal to the dewpoint temperature (T_{DP}), which in turn is determined as a function of temperature (T_{air_ext} = 32ºC) and relative humidity in the external environment (ϕ_{air_ext} = 65%).

Figure 1. Temperature distribution in thermally insulated duct.



Source: Authors (2020).

Figure 2. Equivalent thermal circuit.



Source: Authors (2020).

From the equivalent thermal circuit shown in Figure 2, we have the following equation for heat flow in the thermally insulated duct:

$$q" = \frac{T_{air\_ext} - T_{DP}}{\frac{1}{h_{c\_ext} + h_{r\_ext}}} = \frac{T_{DP} - T_{air\_int}}{\frac{1}{h_{c\_int}} + \frac{L_{duct}}{k_{duct}} + \frac{L_{insu}}{k_{insu}}} \tag{1}$$

where q” is the heat flux, T_{air_ext} = 32ºC, T_{air_int} = 15ºC and T_{DP} = 24.59ºC are external air, internal air and dewpoint temperatures, considering data for the city of João Pessoa. h_{c_ext} and h_{r_ext} are the convection and radiation heat transfer coefficients, respectively, on the external surface of the thermal insulation. h_{c_int} is the convection heat transfer coefficient on the internal surface of the duct. k_{duct} = 52 W/mK and k_{insu} are the thermal conductivity of the duct (galvanized steel) and insulating material, respectively. L_{duct} = 0.7 mm is the duct thickness and L_{insu} is the minimum thermal insulation thickness required to prevent the effect of condensation. Rearranging Equation 1, we have:

$$L_{insu} = k_{insu} \cdot \left[\frac{1}{h_{c\_ext} + h_{r\_ext}} \cdot \left(\frac{T_{DP} - T_{air\_int}}{T_{air\_ext} - T_{DP}} \right) - \frac{1}{h_{c\_int}} - \frac{L_{duct}}{k_{duct}} \right] \tag{2}$$

The convective heat transfer coefficient on the external surface of the thermal insulation is given by Eq. 3, as follows:

$$h_{c\_ext} = \frac{k_f}{L} \cdot \overline{Nu}_L \tag{3}$$

where L = 1.0 m is the characteristic length, which corresponds to the height of the duct sidewall and k_f is the thermal conductivity of the outside air.

Modeling the sidewalls of the duct as vertical flat plates and considering laminar flow ($10^4 \leq Ra_L \leq 10^9$), we used the correlation recommended by Churchill and Chu (1975) to calculate the average Nusselt number, as follows:

$$\overline{Nu}_L = \left\{ 0.825 + \frac{0.387\, Ra_L^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}} \right\}^2 \tag{4}$$

where Pr is the Prandtl number and Ra_L is the Rayleigh number, the latter defined by Equation 5.

$$Ra_L = \frac{g\beta (T_{DP} - T_{air\_ext}) L^3}{\upsilon \alpha} \tag{5}$$

where g is the gravity acceleration, β is the volumetric expansion coefficient, ν is the kinematic viscosity and α is the thermal diffusivity of air. To calculate the values of wet air properties (k_f, Pr, β, ν and α), a methodology proposed by Tsilingiris (2008) was used, valid for temperatures between 0 and 100ºC, and it was considered an altitude of 0 m (sea level).

The radiation heat transfer coefficient on the outer surface of the thermal insulation is calculated using an Equation 6, as follows:

$$h_{r\_ext} = \varepsilon_{insu}\sigma\left(T_{air\_ext} + T_{DP}\right)\left({T_{air\_ext}}^2 + {T_{DP}}^2\right) \tag{6}$$

where ε_{insu} = 0.04 is the emissivity of the insulating material and σ is the Stefan-Boltzmann constant ($\sigma = 5.67\times10^{-8}$ W/(m^2×K^4)).

The convection heat transfer coefficient on the inner surface of the duct (h_{c_int}) was calculated as a function of the Nusselt number for internal and turbulent flow (Cengel, 2014), as follows:

$$h_{c\_int} = \frac{k_{f\_int}}{D_h}\cdot\overline{Nu}_{L\_int} = \frac{k_{f\_int}}{D_h}\cdot 0{,}125\cdot f\cdot Re\cdot {Pr_{int}}^{1/3} \tag{7}$$

where k_{f_int} is the thermal conductivity of the air inside the duct, D_h is the hydraulic diameter of the duct, f is the friction factor, *Re* is the Reynolds number and Pr_{int} is the Prandt number of the air inside the duct. The air velocity inside the duct used to calculate the Reynolds number was 6 m/s.

In order to evaluate the influence of the thermal conductivity (k_{insu}) and emissivity (ε_{insu}) of the insulating material on the minimum thermal insulation thickness necessary to avoid the effect of condensation (L_{insu}), an experimental design was developed.

The actual and coded levels of the experimental design input variables are presented in Table 1, where (-1) and (+1) represent the lowest and highest levels, respectively, and (0) represent the center point level.

Table 1. Actual and coded levels of the input variables under analysis.

Input variables	**Levels**		
	-1	**0**	**+1**
k_{insu} (W/mK)	0.02	0.06	0.10
ε_{insu} (-)	0.04	0.50	0.96

Source: Authors (2020).

As a methodology, an experimental design of type 2^2 was developed with three experiments at the central point, totaling 7 experiments. The experimental design matrix in the so-called standard order as well as the results obtained for the response variable under analysis are presented in Table 2.

Table 2. Experimental design matrix 2^2 with three experiments at the central point and results obtained for the response variable (L_{insu}).

Experiments	**Input variables**		**Response variable**
	k_{insu} (W/m·K)	**ε_{insu} (-)**	**L_{insu} (mm)**
1	0.02 (-1)	0.04 (-1)	8.915
2	0.10 (+1)	0.04 (-1)	44.336
3	0.02 (-1)	0.96 (+1)	2.064
4	0.10 (+1)	0.96 (+1)	10.294
5	0.06 (0)	0.50 (0)	11.083
6	0.06 (0)	0.50 (0)	11.083
7	0.06 (0)	0.50 (0)	11.083

Source: Authors (2020).

From the results obtained from the experimental design matrix, the *STATISTICA*® *7* program was used to calculate the main and interaction effects of the input variables in the response variable. In addition, it was used to assist in the analysis of variance (ANOVA), as well as in obtaining the mathematical model, the response surface and the contour plot, as will be presented.

3. Results and Discussions

Table 3 lists the significance levels (α) and the statistically significant coefficients of the main and interaction factors on the response variable under analysis. At a significance level (α) of 0.05, all factors are considered statistically significant, ie there is a probability of at least 95% accuracy in assuming that these factors influence the L_{insu} response variable.

Significance levels represent the probability of error in accepting that a given factor influences the studied response. As an example, for the effect of thermal conductivity of the insulating material (k_{insu}) on the L_{insu} response variable, this probability is 1.234%. Thus, as the probability of error is less than the default value of 5%, the result is considered statistically significant (Rodrigues & Iemma, 2009).

Table 3. Significance levels (α) and statistically significant coefficients for the response variable under analysis.

Factors	**Significance levels (α)**	**Statistically significant coefficients (α < 0,05)**
Mean	0.00266	14.118
k_{insu}	0.01234	10.913
ε_{insu}	0.01478	-10.223
$k_{insu} \times \varepsilon_{insu}$	0.04327	-6.798

Source: Authors (2020).

Thus, the empirical mathematical model for the L_{insu} response variable, as a function of the coded values of the input variables, as presented in Table 1, is given by Eq. 8, as follows:

$$L_{insu}(mm) = 14.118 + 10.913k_{insu} - 10.223\varepsilon_{insu} - 6.798k_{insu} \times \varepsilon_{insu} \tag{8}$$

From the mathematical model presented above, it is possible to quantify the main and interaction effects of the input variables in the response variable. Thus, it is possible to predict the minimum thermal insulation thickness necessary to avoid the effect of condensation on the duct, as a function of its thermal properties.

The higher the coefficient of a given factor, the greater its contribution to the response variable. Thus, in the proposed range of variation for the thermal properties of the insulating material, as shown in Table 1, the thermal conductivity (k_{insu}) has a slightly higher influence than the emissivity (ε_{insu}) on the L_{insu} response variable.

To use the mathematical model, the coded values for the input variables must be used, according to Table 1, that is, their values may vary from -1 to +1. If it is desired to estimate, for example, the minimum thickness of rockwool blanket with aluminum foil (k_{insu} = 0.0372 W/mK and ε_{insu} = 0.04) necessary to avoid the effect of condensation on the duct, use the Equation 8 with the coded levels, as follows:

$$\begin{aligned} L_{iso}(mm) &= 14.118 + 10.913 \cdot (-0.57) - 10.223 \cdot (-1) - 6.798 \cdot (-0.57) \cdot (-1) \\ &= 14.25 \end{aligned} \tag{9}$$

For the variable ε_{insu}, the coded value -1 was extracted directly from Tab. 1, while for the k_{insu} variable, a linear interpolation between the lower and central levels was performed, obtaining the coded value of -0.57.

Table 4 shows the main results of the analysis of variance (ANOVA) for the L_{insu} response variable. Such results are important in the evaluation of the coefficient of determination (R^2), the statistical significance and the adjustment of the mathematical model obtained from the experimental design.

Table 4. Analysis of variance (ANOVA) for the L_{insu} response variable.

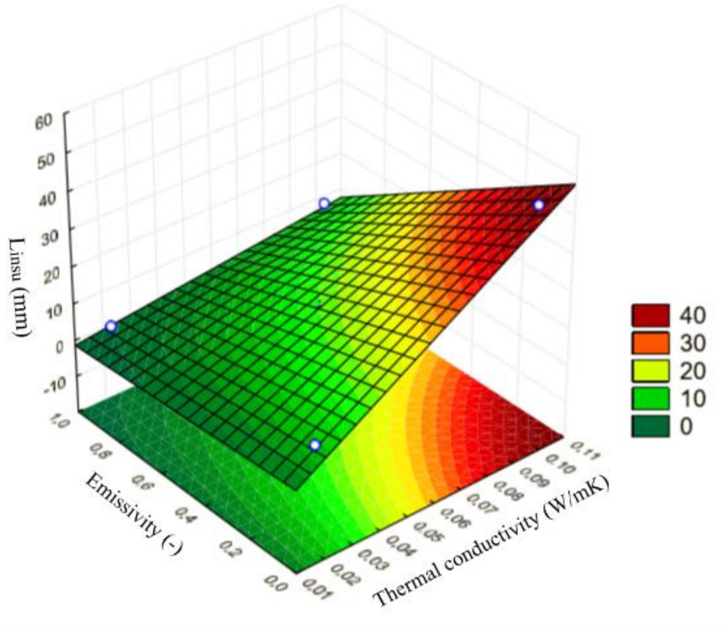
Source of variation	**Sum of squares (S.S)**	**Degrees of freedom (D.F)**	**Means squares (M.S)**	$F_{Calculated}$ **(MQ/MQ$_{Res}$)**	$F_{Tabulated}$
Effect of k_{insu}	476.38	1	476.38	39.29	6.94
Effect of ε_{insu}	418.06	1	418.06	34.48	6.94
Effect of $k_{insu} \times \varepsilon_{insu}$	184.83	1	184.83	15.25	6.94
Regression	1079.28	2	539.64	44.51	6.94
Residual	48.50	4	12.12	1.00	6.94
Lack of fit	45.86	2	22.93	1.89	6.94
Pure error	2.63	2	-	-	-
Total	1127.78	6	-	-	-
Coefficient of determination (R^2)	**95.70%**		-	-	-

Source: Authors (2020).

From the analysis of Table 4, it can be concluded that the model presented a very satisfactory coefficient of determination (R^2) and statistically significant regression, considering that $F_{calculated} > F_{Tabulated}$ was established for regression at the 95% confidence level. In addition, the model is also well adjusted, given that $F_{calculated} < F_{Tabulated}$ for lack of fit. $F_{Tabulated}$ value for regression was determined using the values of the regression and residual degrees of freedom, while $F_{Tabulated}$ value for the lack of fit was determined using the values of the lack of fit and residual degrees of freedom, according to Rodrigues and Iemma (Rodrigues & Iemma, 2009).

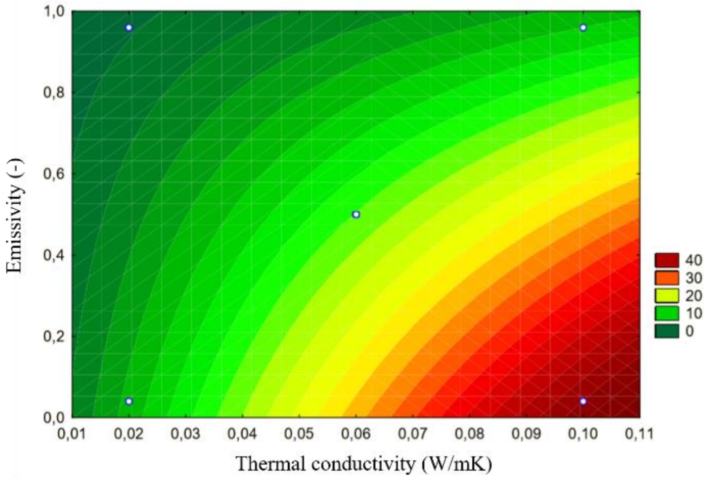
Figures 3 and 4 illustrate, respectively, the response surface and the contour plot for the L_{insu} response variable as a function of the thermal conductivity (k_{insu}) and emissivity (ε_{insu}) of the thermal insulation.

Figure 3. Response surface of L_{insu} as a function of k_{insu} and ε_{insu}.



Source: Authors (2020).

Figure 4. Contour plot of L_{insu} as a function of k_{insu} and ε_{insu}.



Source: Authors (2020).

From the analysis of Figures 3 and 4, it is observed that the lower the emissivity (ε_{insu}) and the higher the thermal conductivity (k_{insu}) of the insulating material, the greater the thickness of thermal insulation required to avoid the effect of condensation on the air conditioning duct (L_{insu}). It is also observed that the influence of emissivity (ε_{insu}) on the response variable increases as the thermal conductivity of the insulating material (k_{insu}) increases.

4. Final Considerations

In view of the results presented, it can be concluded that by analysis of variance (ANOVA), it was possible to determine a mathematical model with very satisfactory coefficient of determination (R^2), well-adjusted and statistically significant regression for the response variable under analysis. Also, the analysis developed by the experimental design methodology was important to prove that the thermal conductivity (k_{insu}) and emissivity (ε_{insu}) of the insulating material influence the minimum thermal insulation thickness necessary to avoid the effect of condensation on air conditioning ducts. Furthermore, in the proposed ranges for the thermal properties of the insulating material, the thermal conductivity (k_{insu}) is the input variable that has the greatest influence on the response variable under analysis.

In view of the importance of this topic, the authors suggest that further research be carried out to assess the influence of other variables on the minimum thickness of thermal insulation necessary to avoid the effect of condensation on air conditioning ducts. Also, numerical computer simulations could be used to study, in more detail, the fluid dynamic behavior of the phenomenon under analysis.

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