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The log mean heat transfer rate method of heat exchanger considering the influence of heat radiation

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ABSTRACT

The log mean temperature difference (LMTD) method is conventionally used to calculate the total heat transfer rate of heat exchangers. Because the heat radiation equation contains the 4th order exponential of temperature which is very complicate in calculations, thus LMTD method neglects the influence of heat radiation. From the recent investigation of a circular duct in some practical situations, it is found that even in the situation of the temperature difference between outer duct surface and surrounding is low to 1 °C, the heat radiation effect can not be ignored in the situations of lower ambient convective heat coefficient and greater surface emissivities. In this investigation, the log mean heat transfer rate (LMHTR) method which considering the influence of heat radiation, is developed to calculate the total heat transfer rate of heat exchangers.

1. Introduction

Heat exchangers are widely applied to the industries and living surroundings. The log mean temperature difference (LMTD) method which introduced in most heat transfer text books [1–8] as well as air conditioning and refrigeration text books [9–12], is conventionally used to calculate the total heat transfer rate of heat exchangers. Because the heat radiation equation contains the 4th order exponential of temperature which is very troublesome in calculations, thus LMTD method neglects the influence of heat radiation. Recently, Hsien et al. [13] studied about the complete heat transfer characteristics of a circular duct considering the heat radiation effect while applying to heat exchanging. From the simulations in some practical situations, it is found that the heat radiation effect can not be ignored in situations of lower ambient convection heat coefficients and greater surface emissivities; even in situations of temperature difference between inner fluid and surrounding ambient air low to 1 °C, the errors generated by neglecting the heat radiation are still very big and unacceptable. In most situations, ignoring the heat radiation will generate big errors and affect the design quality of heat exchanger. Hsien et al. [13] also proved that using greater surface emissivity can greatly improve the performance of heat exchanger.

In this present investigation, the log mean heat transfer rate (LMHTR) method which considering the influence of heat radiation, is developed to calculate the total heat transfer rate of heat exchangers.

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2. Problem formulation

Fig. 1 shows that an circular duct with inner radius r_1, outer radius r_2, duct thickness t_1, duct length L, wall conductivity K_A, surface emissivity ε, is exposed to internal and external fluids with convection heat transfer coefficients h_{i1} and h_{o1} as well as temperatures T_{i1} and T_{o1} at entrance section of the duct, respectively; and it is exposed to internal and external fluids with convection heat transfer coefficients h_{i2} and h_{o2} as well as temperatures T_{i2} and T_{o2} at exit section of the duct, respectively.

2.1. LMTD method neglecting the influence of heat radiation

While the influence of outside surface heat radiation is not considered, the log mean temperature difference (LMTD) method [1–12] is conventionally used to calculate the total heat transfer rate of heat exchangers. From the relative temperatures of entrance and exit sections as shown in Fig. 1, LMTD can be expressed as:

$$\mathrm{LMTD} = \frac{(T_{i1} - T_{o1}) - (T_{i2} - T_{o2})}{\ln\frac{(T_{i1} - T_{o1})}{(T_{i2} - T_{o2})}} \tag{1}$$

The total thermal resistance of the circular duct shown in Fig. 1 can be written as:

$$R_{th} = \frac{1}{h_i 2\pi r_1 L} + \frac{\ln\frac{r_2}{r_1}}{2\pi K_A L} + \frac{1}{h_o 2\pi r_2 L} \tag{2}$$

Nomenclature

ε	emissivity
A_1	inner surface area of a duct
A_2	outer surface area of a bare duct
h_{i1}	inner heat convection coefficient at entrance section
h_{i2}	inner heat convection coefficient at exit section
h_{o1}	outer heat convection coefficient at entrance section
h_{o2}	outer heat convection coefficient at exit section
K_A	conductivity of duct
L	duct length
Q	total heat transfer rate without considering heat radiation
Q_a	total heat transfer rate considering heat radiation
q_1	unit length heat transfer rate neglecting heat radiation at entrance section
q_2	unit length heat transfer rate neglecting heat radiation at exit section
q_{a1}	unit length heat transfer rate considering heat radiation at entrance section
q_{a2}	unit length heat transfer rate considering heat radiation at exit section
q_{c1}	unit length convective heat transfer rate at entrance section
q_{c2}	unit length convective heat transfer rate at exit section
q_{r1}	unit length radioactive heat transfer rate at entrance section
q_{r2}	unit length radioactive heat transfer rate at exit section
QR	error of heat transfer rate generated by neglecting heat radiation
r_1	inner radius of circular duct
r_2	outer radius of circular duct
t_1	thickness of duct
T_{21}	the average surface temperature at the entrance section in situation of considering heat radiation
T_{22}	the average surface temperature at the exit section in situation of considering heat radiation
T_{i1}	temperature of the fluid inside the duct at entrance section
T_{i2}	temperature of the fluid inside the duct at exit section
T_{o1}	temperature of the fluid outside the duct at entrance section
T_{o2}	temperature of the fluid outside the duct at exit section
T_{s1}	the average surface temperature at the entrance section in situation of neglecting heat radiation
T_{s2}	the average surface temperature at the exit section in situation of neglecting heat radiation
T_{sur}	surrounding temperature
TR_1	error of average surface temperature at the entrance section generated by neglecting heat radiation
TR_2	error of average surface temperature at the exit section generated by neglecting heat radiation

The total heat transfer rate of the long circular duct neglecting the heat radiation by LMTD method is:

$$Q = \frac{\mathrm{LMTD}}{R_{th}} \tag{3}$$

The unit length heat transfer rate, q_1, at the entrance section is:

$$q_1 = \frac{T_{i1} - T_{o1}}{R_{th}L} = \frac{T_{S1} - T_{o1}}{\frac{1}{h_o 2\pi r_2}} \tag{4}$$

The unit length heat transfer rate, q_2, at the exit section is:

$$q_2 = \frac{T_{i2} - T_{o2}}{R_{th}L} = \frac{T_{S2} - T_{o2}}{\frac{1}{h_o 2\pi r_2}}, \tag{5}$$

The values of total heat transfer rate Q, the average surface temperature at the entrance section T_{s1}, the average surface temperature at the exit section T_{s2}, can obtained from Eqs. (1)–(5) under the given values of h_i, ($h_i = h_{i1} = h_{i2}$), h_o($h_o = h_{o1} = h_{o2}$), r_1, r_2, K_A, L, T_{i1},T_{o1}, T_{i2}, T_{o2} and L.

2.2. Situations considering the influence of heat radiation

While the influence of outside surface heat radiation is considered, the complete unit length heat transfer rate at the entrance section is:

$$q_{a1} = \frac{T_{i1} - T_{o_1}}{\frac{1}{h_{i1}2\pi r_1} + \frac{\ln\frac{r_2}{r_1}}{2\pi K_A}} \tag{6}$$

The unit length surface convective heat transfer rate at the entrance section is:

$$q_{c1} = h_{o1}2\pi r_2(T_{21} - T_{o_1}) \tag{7}$$

The unit length surface radiation heat transfer rate at the entrance section is:

$$q_{r1} = \sigma\varepsilon 2\pi r_2(T_{21}^4 - T_{sur}^4) \tag{8}$$

The following equation is obtained from heat balance at the entrance section:

$$q_{a1} = q_{c1} + q_{r1} \tag{9}$$

The values of q_{a1}, q_{r1}, q_{c1} and T_{21} can obtained from Eqs. (6)–(9) under the given values of h_{i1}, h_{o1}, r_1, r_2, K_A, L, T_{i1},T_{o1}, ε and T_{sur}.

Similarly, the complete unit length heat transfer rate at the exit section is:

$$q_{a2} = \frac{T_{i2} - T_{o_2}}{\frac{1}{h_{i2}2\pi r_1} + \frac{\ln\frac{r_2}{r_1}}{2\pi K_A}} \tag{10}$$

The unit length surface convective heat transfer rate at the exit section is:

$$q_{c2} = h_{o2}2\pi r_2(T_{2_2} - T_{o_2}) \tag{11}$$

The unit length surface radiation heat transfer rate at the exit section is:

$$q_{r2} = \sigma\varepsilon 2\pi r_2(T_{22}^4 - T_{sur}^4) \tag{12}$$

The following equation is obtained from heat balance at the exit section:

$$q_{a2} = q_{c2} + q_{r2} \tag{13}$$

The values of q_{a2}, q_{r2}, q_{c2} and T_{22} can obtained from Eqs. (10)–(14) under the given values of h_{i2}, h_{o2}, r_1, r_2, K_A, L, T_{i2}, T_{o2}, ε and T_{sur}.

The total heat transfer rate of the long circular duct considering the heat radiation by log mean heat transfer rate (LMHTR) method is:

$$Q_a = \frac{q_{a1} - q_{a_2}}{\ln\frac{q_{a1}}{q_{a2}}}L \tag{14}$$

The above LMHTR method (considering heat radiation) under the same concept as LMTD method (neglecting heat radiation) is developed in this study. While the heat radiation is not considered, assume the temperatures T_{i1} and T_{o1} keep constant at the entrance