Effect of Radiation Heat Transfer on a Bayonet Tube Heat Exchanger

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INTRODUCTION

The main objective of this paper is to present the effect of radiation heat transfer on a bayonet tube heat exchanger, accounting for conduction, convection, and radiation heat transfer. A bayonet tube consists of a pair of concentric tubes. The outer tube is capped at one end, and a gap is left between the bottom of the inner tube and the cap on the outer tube, as shown in Figure 1. The air being preheated flows down the annulus and up the center tube or vice versa. Bayonet tube heat exchangers are well suited for use when there is a large temperature difference between the shell-side and tube-side fluids. This is because the tube assemblies, fastened at only one end and suspended in the high temperature gas stream, are free to expand or contract under the influence of temperature variations.

FORMULATION OF EQUATIONS

In a bayonet tube heat exchanger as shown in Figure 1, R_1, R_2, R_3, and R_4 are the inner and outer radii of the inner and outer tubes, and L is the effective length of the bayonet tube. For a bayonet tube that is divided into N slices, one can assume that the values of the thermal properties used in each slice can be evaluated at the mean temperature of the slice, and that the heat conduction in the axial direction is negligible compared to heat conduction in the radial direction. From an energy balance, the following equations are formulated.

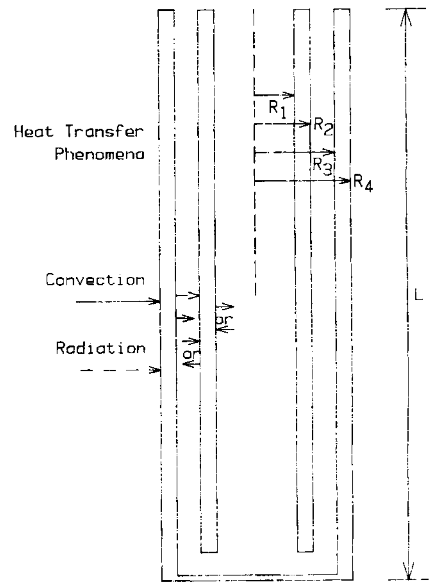

Figure 1. Scheme of a bayonet tube.

Energy Balance on Inner and Outer Tube Walls

$$\left(R_1 h_{1,i} + \frac{k_{I,i}}{\ln\dfrac{R_2}{R_1}}\right) T_{1,i} - \frac{k_{I,i}}{\ln\dfrac{R_2}{R_1}} T_{2,i} - R_1 h_{1,i} T_{C,i} = 0 \quad (1)$$

$$\frac{k_{I,i}}{\ln\dfrac{R_2}{R_1}} T_{1,i} - \left(R_2 h_{2,i} + \frac{k_{I,i}}{\ln\dfrac{R_2}{R_1}}\right) T_{2,i} - R_2 \varepsilon_i \sigma T_{2,i}^4 + R_2 \varepsilon_i \sigma T_{3,i}^4 + R_2 h_{2,i} T_{A,i} = 0 \quad (2)$$

$$- R_2 \varepsilon_i \sigma T_{2,i}^4 + \left(R_3 h_{3,i} + \frac{1}{\dfrac{1}{k_{O,i}} \ln\dfrac{R_4}{R_3} + \dfrac{1}{R_4 h_{4,i}}}\right) T_{3,i} + R_2 \varepsilon_i \sigma T_{3,i}^4 - R_3 h_{3,i} T_{A,i} - \frac{1}{\dfrac{1}{k_{O,i}} \ln\dfrac{R_4}{R_3} + \dfrac{1}{R_4 h_{4,i}}} T_{\mathrm{amb},i} = 0 \quad (3)$$

The temperature mean values are found from

$$T_{j,i} = \frac{1}{\Delta z} \int_{(i-1)\Delta z}^{i\Delta z} T_j dz, \quad (4)$$

where index j refers to radial location, $j = 1, 2, 3$, etc., and index i refers to axial location, $i = 1, 2, 3, \ldots N$.

The equation for the effective emissivity ε_i for concentric infinite gray cylinders is:

$$\varepsilon_i = \frac{1}{\dfrac{1}{\varepsilon_{2,i}} + \dfrac{R_2}{R_3}\left(\dfrac{1}{\varepsilon_{3,i}} - 1\right)}$$

Energy Balance on Fluid

For the case where the fluid enters the annulus and exits through the inner tube

$$\frac{dT_A}{dz/L} + \alpha_i T_A = \alpha_{1,i} T_2 + \alpha_{2,i} T_3 \qquad (5)$$

and

$$-\frac{dT_C}{dz/L} + \beta_i T_C = \beta_i T_1 \qquad (6)$$

Boundary conditions: at $z = 0$, $T_A = T_{A_O}$.

The dimensionless parameters are:

$$\alpha_i = \frac{2\pi L(R_2 h_{2,i} + R_3 h_{3,i})}{\dot{M} c_{pA,i}}, \qquad \beta_i = \frac{2\pi R_1 L h_{1,i}}{\dot{M} c_{pC,i}} \qquad (7)$$

$$\alpha_{1,i} = \frac{2\pi R_2 L h_{2,i}}{\dot{M} c_{pA,i}}, \qquad \alpha_{2,i} = \frac{2\pi R_3 L h_{3,i}}{\dot{M} c_{pA,i}} \qquad (8)$$

where $i = 1, 2, 3, \ldots N$.

In a similar manner, one can formulate the case where the fluid enters the inner tube and exits through the annulus.

ANALYSIS

By the techniques of integration and finite-difference equation, one can solve for the fluid temperatures in terms of the tube wall temperatures. When these fluid temperatures are substituted into Eqs. 1–3, one can obtain a set of $3N$ nonlinear equations with $3N$ unknowns ($T_{1,i}$, $T_{2,i}$, $T_{3,i}$, $i = 1, 2, 3, \ldots N$). The solution is obtained by an iterative procedure. The Newton-Raphson method is used to solve the $3N$ nonlinear equations for the wall temperatures. The fluid temperatures can be found from these obtained wall temperatures; the details are given by Li (1981).

RESULTS AND DISCUSSION

In order to demonstrate the effects of the radiation heat transfer as well as variable thermal properties of a fluid in a bayonet tube, a numerical example for a bayonet tube heat exchanger with air to be preheated is computed using the following data:

R_1	$= 0.1$ m	$\varepsilon_{2,i}$	$= 0.8$
R_2	$= 0.105$ m	$\varepsilon_{3,i}$	$= 0.8$
R_3	$= 0.12$ m	$k_{O,i}$	$= 20.77$ W/m · K
R_4	$= 0.125$ m	$k_{I,i}$	$= 20.77$ w/m · K
L	$= 3.25$ m	T_{A_O}	$= 20°$C
$\dot{M}$	$= 0.1$ kg/s	T_{amb}	$= (968.3 + 278\ z/L)$
N	$= 10$		

Figure 2 compares the fluid temperature distribution along the bayonet tube with and without radiation heat transfer between the annulus walls for the fluid entering the annulus and exiting through the central tube. Figure 2 also shows that the annulus fluid temperature distributions with and without radiation heat transfer are almost the same. From this figure it can be concluded that intertube radiation has more of an impact on the center fluid temperature than on the annulus fluid temperature.

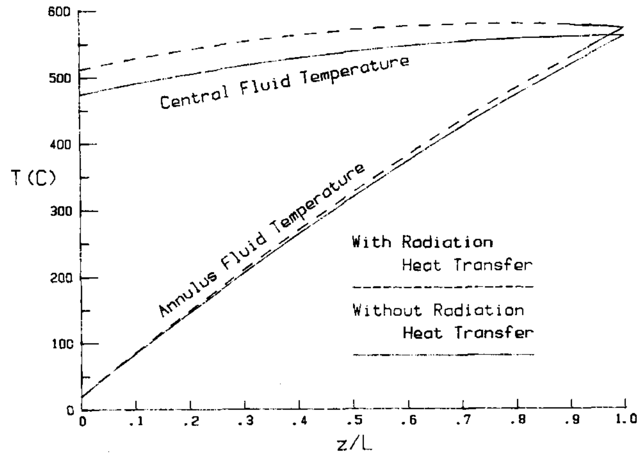

Figure 2. Comparison of fluid temperature distribution with and without radiation heat transfer.

Figures 3 and 4 show the temperature distributions of the tube wall and the fluid for the case of the fluid entering the annulus both neglecting and including intertube radiation. The inner tube wall temperatures in Figure 3 are between the temperatures of the center fluid and the annulus fluid, which indicates that heat transfer is primarily by conduction (through the tube) and convection (to the fluids). The inner tube wall temperatures shown in Figure 4 lie between the temperatures of the center fluid and annulus fluid in low ambient temperature zones, but they are higher than the center fluid and annulus fluid temperatures in high ambient temperature zones. This shows that radiation heat transfer is important in these regions. It is also interesting to note that in Figure 4 the inner tube wall temperatures can be larger than either of the surrounding fluid temperatures near the bottom of a bayonet tube.

For the case of the fluid entering the annulus, Figure 2 shows that the maximum fluid temperature is at the bottom of the tube ($z = L$) if intertube radiation is neglected, and at $z = 0.76L$ inside the inner tube if intertube radiation is included. Without intertube radiation, heat is transferred from the center fluid to the inner tube, hence the maximum fluid temperature occurs at the bottom of a bayonet tube. With intertube radiation, as shown in Figure 4, the center fluid

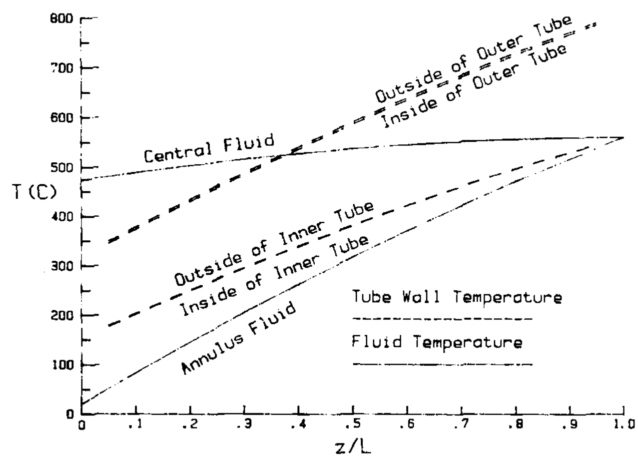

Figure 3. Temperature distribution of tube wall and fluid without radiation heat transfer.

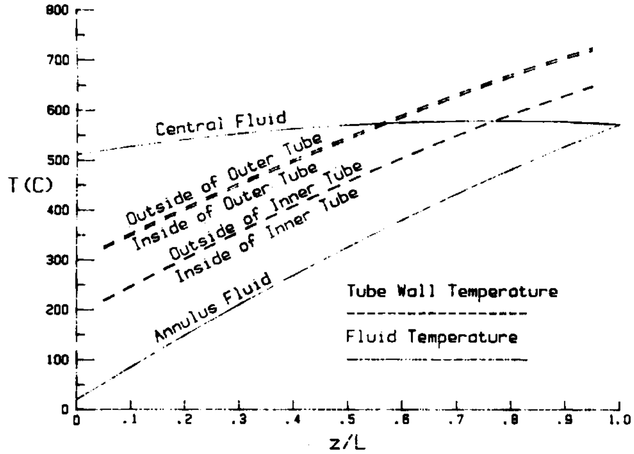

Figure 4. Temperature distribution of tube wall and fluid with radiation heat transfer.

temperature can be heated up by convection from the inner tube from the bottom to $z = 0.76L$.

CONCLUSION

This study has shown:

1. Radiation effects have more impact on the center tube fluid temperature than on the annulus fluid temperature.
2. As a result of intertube radiation, the inner tube wall temperature can exceed the surrounding fluid temperature when tube temperatures are high.

NOTATION

c_p = specific heat of tube-side fluid, J/kg · K
h = heat transfer coefficient, W/m^2 · K
k = thermal conductivity, W/m · K
L = effective length of bayonet tube, m
$\dot{M}$ = flow rate of tube-side fluid, kg/s
N = number of axial slices into which the tube is divided
R = radius, m
T = temperature, K
Δz = length of a slice, m

Greek Letters

α = dummy variable defined by Eqs. 7 and 8
β = dummy variable defined by Eq. 8
ε = surface emittance
σ = Stefan-Boltzmann constant, 5.6688×10^{-8}W/m^2 · K^4

Subscripts

A = annulus fluid
amb = ambient fluid
C = center fluid
i = axial location, i.e., slice number
I = inner tube wall
j = radial location
O = outer tube wall

LITERATURE CITED

Li, C. H., "Analytical Solution of the Heat Transfer Equation for a Bayonet Tube Heat Exchanger," *Paper No. 81-WA/NE-3*, ASME Winter Ann. Meet., Washington, DC (1981).

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