Abstract

Direct air cooling system has some problems. Such as, exhaust steam pressure increased with ambient temperature (dry bulb temperature) rising, furthermore cause the high coal consumption of power supply, heavy pollution, the weak environmental adaptability. To solve above problems, the literature [1] puts forward a new indirect air cooling system. In this system, water cooling steam-condenser is transformed into ammonia phase change heat exchanger whose structure is similar to shell-and-tube heat exchanger. In the tube, ammonia-liquid displaces cooling water of water cooling steam-condenser. Latent heat of ammonia-liquid can improve steam condensation effect. Ammonia phase change heat exchanger is simplified as a single horizontal tube. Simulate ammonia-liquid flowing in it by FLUENT. Shah’s heat transfer model for boiling region is used to predict heat transfer coefficient. Compare the predicted with numerical value what calculated by FLUENT. Prove the feasibility of composite air-cooling circulatory system.

© 2012 Published by Elsevier Ltd. Selection and/or peer-review under responsibility of Hainan University.

Keywords: ammonia phase change heat exchanger; in tube boiling; heat transfer coefficient; Mixture model of FLUENT; phase change heat transfer

1. Problem Description

Vapor is condensed to water outside horizontal tube, and at the same time, ammonia-liquid is boiling in the tube. The diameter of tube is 0.01m, length is 12m. The Vapor and ammonia-liquid are both saturated. Saturated temperature of vapor is 32.5°C, ammonia-liquid’s saturated temperature is 27.5°C. Invariable wall temperature; 0.1m/s for velocity inlet; pressure outlet; Mixture model and need to define mass and energy sources; compile UDFs; make use of k-ε model; Pressure-Velocity Coupling select SIMPLE; Properties of ammonia-liquid and ammonia-vapor both are corresponded saturated temperatures 27.5°C. In the velocity inlet, the volume fraction of ammonia-vapor equal to 0.
2. The Method of Numerical Simulation

The fluid flow and heat transfer inside a horizontal tube is a complex two-phase flow and phase change heat transfer process. In the tube, due to boiling and the change of pressure, the simulation needs to figure out the transfer of mass and energy between two phases. Whether accurately define mass and energy sources, it is critical for successful simulation.

Transfer rate \( Q_{lg} \), what occurs at liquid-vapor interface, is described by convective heat transfer coefficient at interface \( h_{lg} \), the specific surface area \( A_{lg} \) and the part temperature difference in control volume. \( A_{lg} \) can be work out by Nusselt number Correlation. When bleb flows in the incompressibility Newtonian fluid, Nusselt number at interface can be described by the bleb flow Reynold's number \( Re_b \) and \( Pr \) of liquid, the correlation [2] as follow,

\[
Q_{lg} = \alpha h_{lg} A_{lg} \left[ T - T_{sat} \right]
\]

FLUENT help text offers energy source, form as follow,

\[
S = 0.1 \alpha \rho \frac{\Delta T}{T_{sat}}
\]

Here, defining mass and energy sources[3] need to tie in with the facts. During energy transfer, according to law of conservation of energy, the physics signification of sources is the transfer energy in unit time and unit cubage. W/m² is the unit of S(second).

2.1. Using Iteration Work out the Final Wall Temperature.

FLUENT provides data for iteration. And then work out the final wall temperature. Because of wall temperature between 27.5°C and 32.5°C, we need to fix on wall temperature by iteration. Initialization of wall temperature is 32.5°C. If the transfer rate difference between two near iterations below 1%, we consider wall temperature of the two near iterations are equivalency. The wall temperature of the last iteration can be considered equal to the actual wall temperature.

![Flow chart](image-url)
Initial Value: Saturated vapour temperature is 32.5. Using Nusselt equation:
\[ \alpha = 0.725 \left[ \frac{3 \lambda h (1 - \rho_v) \Delta T_0}{\eta (T_{sat} - T_w) d} \right]^{1/4} \] [4],
work out \( \alpha_{H_2O} = 11310.05 \text{ W/m}^2 \).

Heat Transfer area: \( A = \pi \cdot d \cdot l = \pi \cdot 0.01 \cdot 12 = 0.377 \text{ m}^2 \).

Assume initial value of Wall Temperature is 32.5°C, viz., when \( i = 0 \), \( t_{w_i} = t_{w_0} = 32.5°C \). Recur to numerical calculation which offered by FLUENT, obtain the value of \( \alpha_{NH_3,i} \), and then, obtain total heat transfer coefficient of wall at the \( i \) time iteration by the follow formula:
\[ \alpha_{toti} = \frac{\alpha_{H_2O}}{\alpha_{H_2O} + \alpha_{NH_3,i}} \]

Working medium temperature of inlet is 27.5°C, vapor temperature is 32.5°C, using the follow formula, figure out \( \Delta t_{mi} \):
\[ \Delta t_{mi} = \frac{(32.5 - 27.5) - (32.5 - t_{outi})}{\ln \left( \frac{32.5 - 27.5}{32.5 - t_{outi}} \right)} = \frac{5 - (32.5 - t_{outi})}{\ln \left( \frac{32.5 - t_{outi}}{32.5 - 27.5} \right)} \]

And then get \( Q_{sgli} = \alpha_{toti} \cdot \Delta t_{mi} \cdot A \)

At last, work out wall temperature at the \( i+1 \) time iteration:
\[ t_{w_{i+1}} = t_{w_i} - \Delta t_{outi} \]

If transfer rate difference between two near iteration of single horizontal tube less than 1%, we consider iteration is end. The wall temperature of last iteration is the final wall temperature.

Result as follows:

<table>
<thead>
<tr>
<th>Properties</th>
<th>( i )</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{wi} )</td>
<td>°C</td>
<td>32.5</td>
<td>32.044</td>
<td>31.99</td>
</tr>
<tr>
<td>( \alpha_{NH_3} )</td>
<td>W/(m²·K)</td>
<td>2762.788</td>
<td>2579.868</td>
<td>2539.153</td>
</tr>
<tr>
<td>( \alpha_{toti} )</td>
<td>W/(m²·K)</td>
<td>2220.396</td>
<td>2100.692</td>
<td>2073.617</td>
</tr>
<tr>
<td>( t_{outi} )</td>
<td>°C</td>
<td>31.670</td>
<td>31.202</td>
<td>31.160</td>
</tr>
<tr>
<td>( \Delta t_{mi} )</td>
<td>°C</td>
<td>2.322</td>
<td>2.745</td>
<td>2.779</td>
</tr>
<tr>
<td>( \Delta t_{outi} )</td>
<td>°C</td>
<td>nonexistence</td>
<td>0.456</td>
<td>0.510</td>
</tr>
<tr>
<td>( Q_{sgli} )</td>
<td>W</td>
<td>1944.035</td>
<td>2174.174</td>
<td>2172.599</td>
</tr>
<tr>
<td>( \Delta Q_i )</td>
<td>%</td>
<td>nonexistence</td>
<td>11.840</td>
<td>0.0725</td>
</tr>
</tbody>
</table>

From table 1, \( \Delta Q_2 = 0.07246\% \), iteration is end. The final wall temperature can be identified. It is 31.99°C.
2.2 Compare Heat Transfer Coefficients to Verify FLUENT Simulate

A brief rundown of Shah’s boiling correlation[5]:

\[
\psi = \frac{a}{a_i}, \quad C_o = \left(\frac{1-x}{x}\right)^{0.8} \\
\left(\frac{\rho_v}{\rho_l}\right)^{0.5}, \text{Bo} = \frac{q}{G_r}, \text{Fr}_1 = \frac{G^2}{(\rho_l^2 g D)} ,
\]

\[
a_i = 0.023 \times \left[ GD \left(1 - x \right) / \eta_l \right]^{0.8} \text{Pr}_1^{0.4} \lambda_l / D
\]

\(a_i\) is the inner surface heat transfer coefficient of wall, when there is no phase change, only ammonia-liquid in the tube.

For horizontal tube:

\[
N = \begin{cases} 
C_o, \text{Fr}_1 > 0.04 \\
0.38 \text{Fr}_1^{-0.3} C_o, \text{Fr}_1 < 0.04
\end{cases}
\]

When \(N > 1\),

\[
\psi = \max(\psi_{nb}, \psi_{cb})
\]

\[
\psi_{nb} = 1 + 46 \text{Bo}^{0.5} \begin{cases}
230 \text{Bo}^{0.5}, \text{Bo} \geq 3 \times 10^{-5} \\
1 + 46 \text{Bo}^{0.5}, \text{Bo} < 3 \times 10^{-5}
\end{cases}
\]

\[
\psi_{cb} = 1.8 / N^{0.8}
\]

When \(0.1 < N < 1\),

\[
\psi = \max(\psi_{bs}, \psi_{cb})
\]

\[
\psi_{bs} = F \text{Bo}^{0.5} \text{e}^{2.74 / N^{0.1}}
\]

\[
F = \begin{cases} 
14.7, \text{Bo} \geq 1.1 \times 10^{-3} \\
15.43, \text{Bo} < 1.1 \times 10^{-3}
\end{cases}
\]

\(\psi_{cb}\) ditto mark.

When \(N < 0.1\),

\[
\psi = \max(\psi_{bs}, \psi_{cb})
\]

\[
\psi_{bs} = F \text{Bo}^{0.5} \text{e}^{2.74 / N^{0.15}}
\]

\(F \& \psi_{cb}\) ditto mark.

\(\psi_{bs}\): \(\psi\) of bubble suppression ;

\(\psi_{cb}\): \(\psi\) of convective boiling;

\(\psi_{nb}\): \(\psi\) of nucleate boiling.

\(Q_{fluent} = 2172.599 W, \quad A = 0.377 m^2.\) Due to thermal resistance, effective heat of the wall is great than transfer rate of single horizontal tube. Here, use transfer rate instead of effective heat. So, the heat flux \(q:\)

\[
q = \frac{Q_{fluent}}{A} = 5762.862 W / m^2.
\]

Using Shah’s boiling correlation, work out heat transfer coefficient:

\[
\alpha' = 2135.164 W / (m^2 \cdot K)
\]

Through FLUENT simulate,

\[
\alpha_{NH_3} = 2073.6174 W / (m^2 \cdot K).
\]
Compare with predicted heat transfer coefficient what offered by Shah’s boiling correlation with the stimulant result by FLUENT, the margin of difference is 2.90%, is less than 14%. The simulation by FLUENT is credible.

3. Conclusion

There are two innovations. The first is proposed based on the Mixture model, simulate horizontal tube boiling heat transfer of liquid ammonia. Second, FLUENT offers data for the iteration, and then using the iterative method to determine the actual wall temperature. Use Shah’s heat transfer model for boiling to predict and compare the predicted heat transfer coefficient in the tube with simulative result, the difference is less than 14%. Take into account when calculating heat flux, transfer rate instead of heat rate, it will result in a reduction in heat transfer coefficient. If use heat rate, will increase heat transfer coefficient, the difference between simulated and predicted will further reduce. Thus, numerical simulation on ammonia- liquid in horizontal tube boiling is reliable, and ammonia phase change heat exchanger has good heat transfer effect. This paper lays the foundation for follow up further study, such as the design for double tube pass ammonia phase change heat exchanger, or increase the difference in temperature between vapor and ammonia.

DEFINITIONS, ACRONYMS, ABBREVIATIONS:

- $\alpha_{H_2O}$: Heat Transfer coefficient of vapor.
- $A$: Heat Transfer area. It is equal to wall area of single horizontal tube.
- $t_{w1}$: Wall temperature at the i time iteration.
- $\alpha_{NH_3i}$: Inner surface heat transfer coefficient of wall at the i time iteration.
- $\alpha_{totali}$: Total Heat Transfer coefficient of wall at the i time iteration.
- $t_{outi}$: Temperature of working medium in the pressure-outflow.
- $\Delta t_{mi}$: Logarithmic mean temperature difference at the i time iteration.
- $Q_{sli}$: Transfer rate of single horizontal tube at the i time iteration.
- $\Delta t_{outi}$: Temperature difference between wall and vapor,

$$\Delta t_{outi} = \frac{Q_{sli}}{\alpha_{H_2O} \cdot A}$$

- $\Delta Q_{i}$: Transfer rate difference between two near iteration of single horizontal tube.

$$\Delta Q_{i} = \frac{Q_{sli} - Q_{sli+1}}{Q_{sli}} < 1\%$$

$Q_{sli}$: Final transfer rate of single horizontal tube, unit is W.

Acknowledgment

I want to express my sincere respect and thanks to my tutor Associate Professor Wang. This paper is completed under the guidance of Shenglong Wang. Using his profound knowledge, he is glad to give advice and assistance to my research. His rigorous research attitude affects my life.

References


