Modelling and Optimization of Heat Transfer in Smooth Circular Tube Used in the Shell and Tube Evaporator

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Abstract: - An optimization of heat transfer for smooth circular tube used in an evaporator of the ammonia-water absorption cooling system has been carried out to estimate minimum outlet water temperature and maximum heat flux. The tube diameter ranges from 7 to 13 mm and length ranges from 0.5 to 1.2 m, has been varied to study the effects. The numerical analysis was performed by using the finite elements commercial code. The optimization result has shown that 7 mm diameter and 1.2 m length has given the minimum water temperature of 8.3 °C at the outlet with maximum heat flux of 16193 W/m².

Key-Words: - heat transfer, fluid flow in pipes, evaporator, heat flux, simulation of single phase flow, minimum outlet water temperature.

1 Introduction

The evaporator is one of the basic and the most important part of the absorption cooling system. In this study, the shell and tube heat exchanger is used as an evaporator. The tubes inside the evaporator provide the heat flux surface between the water flowing inside the tube and the spray liquid of ammonia flow over the tubes. However, to design and optimize the evaporator based on the minimization of refrigerant charge and the cost of running the system is still a challenging task. Lot of studies and researcher in this field were reported for different applications. They have been studied the behavior of the fluid flow inside and outside the pipes with inlet geometry for free and force convection, also demonstrated the effects of the boundary sub layer on the heat transfer coefficient and the average heat flux [1,2,3,4,5,6]. The previous studies didn't report or investigate the outlet temperature and the average heat flux along the tube. Therefore, the aim of this study is to optimize the design parameter of the horizontal smooth pipe which is used inside the evaporator.

2 The Design Parameters

The design parameter for the tube in the shell and tube heat exchanger used at the proposed evaporator of 1.5 ton refrigeration of the absorption cooling system is explained in Fig.1. The effect of the tube diameter and lengths have been studied to achieve the optimum heat flux and to obtain the minimum water temperature from the tube outlet. The design parameters are studied for constant mass flow rate in the tube.

![Figure 1. Model of tube in the heat exchanger](image)

3 Numerical Method

A COMSOL Multiphysics 3.5a is employed to solve this case of study. It is a powerful interactive environment for modeling and solving all engineering and scientific problems based on partial differential equations. COMSOL Multiphysics used Finite Element Method to solve the model. The software runs the finite-
element analysis together with adaptive meshing and error by using different numerical solver. [7]. The direct SPOOLES solver has been applied, which used stationary analysis type with the non linear solver system. A mesh is a partition of the geometry model into small units of simple shapes. In this study 3D geometry are used with a free mesh, fine meshing the number of degree of freedom is 536118 and number of mesh points 25443. Fig.2 It shows the mesh statistic, and Fig.3 It shows the temperature profile and the velocity profile for the fluid flow inside 3D axisymmetric pipe model.

4 The Mathematical Model

The heat and fluid flow analyzed using the equations

4.1 The energy equation

The fundamental law governing the heat transfer is the first law of thermodynamics, which involve the principle of conservation of energy. The basic law is usually rewritten in term of temperature; \( T \) for a fluid, the resulting energy equation is stated as below:

\[
\rho C_v \frac{\partial T}{\partial t} + (u \nabla)T = -(\nabla q) + \tau : S - \frac{T}{\rho} \frac{\partial \rho}{\partial t} \frac{\partial p}{\partial t} + (u \nabla) p + Q \tag{1}
\]

By using Fourier's Law of conductions, the conductive heat flux, \( q \), is proportional to the temperature gradient:

\[
q_i = -k \frac{\partial T}{\partial x_i} \tag{2}
\]

Insert equation (1) into equation (2) and rearranging the terms, ignoring the viscous heat and pressure gradient, the energy equation can be written in the form:

\[
\rho C_v \frac{\partial T}{\partial t} + \rho C_v u \nabla T = \nabla (k \nabla T) + Q \tag{3}
\]

4.2 The Continuity and Momentum Equations

The equations 4, 5, and 6 which are represented continuity equation, the conservation of momentum, and
the conservation of energy these three equations represent
the Navier-Stokes equations for flow of the single-phase
fluid.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]  

(4)

\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \nabla \cdot \mathbf{\tau} + F
\]  

(5)

\[
\rho C_v \left( \frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T \right) = -\nabla \cdot \mathbf{q} + \frac{\partial \rho}{\partial t} \frac{\partial p}{\partial t} + (u \cdot \mathbf{\tau}) + Q
\]  

(6)

Where

- \( \rho \): Density (kg/m\(^3\))
- \( C_v \): Specific heat capacity (J/(kg.K))
- \( T \): Absolute temperature (K)
- \( \mathbf{u} \): Velocity vector (m/s)
- \( q \): Heat flux by conduction (W/m\(^2\))
- \( P \): Pressure (pa)
- \( \mathbf{\tau} \): Viscous stress tensor (pa)
- \( S \): Strain rate tensor: \( 1/2(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \) (1/s)
- \( Q \): Heat sources other than viscous heating (W/m\(^3\))

4.3 The Boundary Conditions

The boundary conditions have been considered. The fluid
temperature at the inlet of the tube is 293.15 K. The
average means velocity change from 0.34 to 0.0662 m/s
according to the difference of inner diameters (7-13) mm.
The temperature on the pipe's wall is constant and equal
to 278.15 K. since the temperature of the evaporation is
constant. The convective heat flux is applied to the output
flow in the circular tube. The only mean of heat transfer
across the boundary is by convection, and conduction.
The temperature gradient in the normal direction is zero
and there is no radiation [7]. The no-slip boundary
condition of the flow on the inner wall of the pipe is
considered. The fluid is considered as Newtonian, and
incompressible. The physical properties of the fluid in the
pipe are varied and temperature dependent. The flow
inside the pipe is considered laminar with different
Reynolds number from 1141 to 2089. The temperature
and velocity profile is simultaneously developed.
Incompressible Navier-Stokes equations with convection
and conduction module are used in the simulation. The
inner diameter range from 7 to 13 mm and the lengths
from 0.5 to 1.2 m are used. The overall flow rate is
0.1197 Kg/s. the thickness of the tube is 1 mm, according
to the standard design. A steel AISA 4340 has been used
for the pipe material.

5. Results and Discussion

The effect of the design parameters (Diameter and Length
of the tube) on the heat transfer coefficient and fluid flow
inside the pipe has been studied. As mentioned previously
the flow inside the pipe is laminar and the case study
assumes the flow inside the tube is not fully developed
according to the calculation of velocity entry length and
thermal entrance length. The effect of diameter and length
are discussed.

5.1 Effect of the tube lengths and diameters on the
heat flux

The average heat flux results for different lengths and
diameters are presented in Fig. 4 and Fig. 5 the results
show that the design with 7 mm and length 0.5 m gives
the highest average heat flux for the certain mass flow
rate. The results also show that as the length of the tube
becomes longer, the average heat flux decreases due to
the development of the temperature profile along the tube.
The results show smallest tube diameter gives more heat
flux along the tube, since higher Reynolds number, due to
higher inlet velocity of the fluid inside the tube.

Figure 4. Variation of heat flux at different tube diameter
5.2 Effect of tube diameter and length on the fluid outlet temperature.

The effect of the tube diameter and the length have been shown in Fig. 6 and Fig. 7. The minimum outlet temperature from the tube can achieve with the smallest tube diameter 7 mm and the longest tube of 1.2 m, since higher velocity and larger surface area, which conducted better heat transfer coefficient. Furthermore, Fig 6 and Fig 7 shows the effect of the varying in length of small diameter 7 and 9 mm is smaller when it is comparing with the wider diameter of 10 and 13 mm. This because the flow inside the small diameter has larger Reynolds number for the same amount of flow rate. And the effect of hydraulic fully development is slighter.

5.3 Effect of tube diameter and length on the pressure drop

The pressure drop along the tube for different diameter has been presented. In figure 8 the pressure drop is a quantity of interest in the analysis of pipe flow. It is directly related to the power consumed in the pump. In this study, the effect of the diameter and the length are explained for the constant mass flow rate inside the tube. The higher pressure drop appears within the smallest and longest tube which is 7 mm diameter and 1.2 m, and this phenomenon can be explained and approved according to the Darcy equation

$$\Delta P_e = f \frac{L \rho V_{avg}^2}{2D}$$

Where $\rho V_{avg}^2$ is the dynamic pressure and $f$ is the Darcy friction factor. Since the amount of the flow rate is constant. The velocity increases as the diameter decrease, also the length is proportional to the pressure drop. The increase in the length leads to increase in the pressure drop.
6 Conclusion

Numerical analysis and optimization of heat and fluid flow for circular smooth tube has been investigated. As well, the effects of tube diameters and lengths were studied. Results demonstrated that the maximum heat flux occurs within the smallest tube diameter and shortest length at constant wall temperature and flow rate. The temperature outlet from the tube has been presented, and the lowest value founded within the smallest tube diameter 7 mm and the longest length of the tube 1.2 m. The present study can be reported to monitor and evaluate the performance of difference kinds of shell and tube evaporators and to optimize the design by using the benefit of optimum heat flux from the individual pipe's wall.

References:


