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Effect of tube arrangement and condensate flow rate on the pressure loss for cross flow of steam in small tube bundle

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ABSTRACT

This research aims to study the effect of tubes arrangement in the presence of condensate inundation, on steam flow resistance in a small tube bundle. In this study, a steam condenser simulation using an air flowing over tubes with artificial water as condensate is considered. The effect of vapor suction on the pressure drop is ignored. Two staggered tube arrangements are tested experimentally: a conventional staggered tube arrangement with equal transverse pitches and equal longitudinal pitches, and a suggested tube arrangement having the same dimensions as the conventional arrangement but with variable pitch. The space between pipes for the last row is kept constant for the two types of tubes arrangement.

The effect of transverse pitch variation and condensate inundation on the pressure drop is quantified experimentally. Numerical calculations were carried out on a one-dimensional model of tube banks for the two arrangements. The adapted value of pressure drop coefficient ζ obtained experimentally was used.

1. Introduction

In designing the condenser tube arrangement, it is to consider the drop in the saturation temperature resulting from a pressure loss caused when steam passes through tube bundle. This drop in saturation temperature due to pressure loss is considered a great factor affecting the condenser performance. Design for minimum pressure drop to avoid loss of temperature driving force is the over-whelming consideration in the case of vacuum condensers. Particularly severe steam side pressure losses were measured in one design of under slung condenser. Row et al. [1] showed that, the steam was unable to reach the lower part of the tube nests because of the frictional resistance of the upper tubes. Removal some of the tubes will give more penetration depth to steam and is improved the vacuum. The fall in steam pressure may be relived by widening the pitch over the upper tube rows. Shell-side pressure drop can be effectively adjusted by the tube pitch variation [2].

The values for pressure drop are difficult to be obtained in real condensers. The condition of steam flowing in a condenser in the presence of the condensate inundation could be simulated by using air flowing over tubes with artificial water [3]. Roques et al. [4] reported that in real condenser the value of condensate flow rate is variable over the cross section of the condenser. The space between tubes is decreased due to the condensate. In addition, the effect of tube spacing on flow transition has been investigated.

Lee et al. [5,6] and Murase et al. [7,8] simulated condensation processes by using air flowing over porous tubes with suction. They found at all Reynolds numbers, except for the lowest in the staggered bundle, that the pressure loss coefficient with suction is independent of suction.

Paisarn et al. [9] presented heat transfer and pressure drop characteristics in horizontal double pipes with helical ribs. Cold and hot water are used as working fluids in the shell and tube side, respectively. It is found that the helical ribs have a significant effect on the heat transfer and pressure drop augmentations.

Sarma et al. [10] have analyzed the influence of turbulence in the condensate film. Their results were based on the assumption that the friction coefficient in condensing flows is identical to that of the single-phase flow.

Bodius et al., Burnside et al. and McNeil et al. [11–13] reported that shell-side pressure drop is a very important variable in the successful design of condensers and the results reported here suggest that considerable errors in pressure drop can result from ignoring the effect of suction. The description of this pressure drop through horizontal tube banks, with condensation, has long been a problem facing design engineers. Modern electric utility steam condensers operate at steam velocities up to 50 m/s, $Re > 10{,}000$. On these arguments, it is safe to continue using dry pressure loss coefficient in staggered bundle design and prediction until the steam velocity drops to below about 20 m/s. However, more experiments are required to clarify the situation and provide reliable correlations. These correlations are included the effect of flow rate, suction, and configuration.

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Nomenclature

A	heat transfer surface area per unit volume, m^2/m^3
C	the vapour condensed on a tube, $kg/m^3/s$
D	tube outside diameter, m
D_{in}	tube inside diameter, m
D_p	the coefficient of diffusion in gas, m^2/s
F	friction factor
h_{fg}	latent heat of condensation, kJ/kg
g	acceleration due to gravity, m/s^2
I	inundation flow rate, kg/m s
k	overall heat transfer coefficient, W/m^2 s
L	tube length, m
m	condensation rate per unit volume, kg/m^3 s
N	number of tube rows
Nu	Nusselt number
P	pressure, N/m^2
p_s	steam pressure, N/m^2
Pr	cooling water Prandtl number
Δp	pressure drop, N/m^2
R	gas constant, kJ/kg K
R_s	steam constant, kJ/kg K
R_g	air constant, kJ/kg K
R_c	condensate thermal resistance, m^2 K/W
R_f	fouling resistance, m^2 K/W
R_t	tube wall thermal resistance, m^2 K/W
R_w	cooling water thermal resistance, m^2 K/W
Re	Reynolds number, $\rho\mu_{\max}D/\mu$
Re_s	Reynolds number of steam flow
S_T	transverse pitch, m
S_{TF}	front transverse pitch, m
S_{TR}	rear transverse pitch, m
S_L	longitudinal pitch, m
T	temperature, K
T_I	interface temperature, K
T_m	mixture temperature, K
T_w	wall temperature, K
U	velocity in main flow direction, m/s
W	the condensate leaving a tube, $kg/m^3/s$
x	main flow direction coordinate, m

Greek symbols

λ	thermal conductivity, W/m K
λ_c	condensate thermal conductivity, W/m K
λ_{cw}	cooling water thermal conductivity, W/m K
λ_t	wall thermal conductivity, W/m K
ζ	pressure drop coefficient per meter in flow direction, 1/m, Eq. (1)
ζ	pressure drop coefficient per row, $\Delta p/(\rho\mu^2_{\max}/2N)$
μ	dynamic viscosity, kg/m s
μ_c	condensate dynamic viscosity, kg/m s
ρ	density, kg/m^3
ρ_c	density of the condensate, kg/m^3
ρ_c	density of the steam, kg/m^3

Subscripts

c	condensate
cw	cooling water
g	gas constant
in	inner
I	interface
m	mixture
max	maximum velocity based on the minimum flow area between tubes
o	approach to the test section
p	diffusion in gas
s	steam
w	wall
th	thermal
v	vapor

Condensation causes two distinct kinds of modification to the pressure losses in tube banks. Firstly, the migration of vapor to the tube surface results in vapor "suction". Lee et al. [5,6] studied the effect of vapor suction on the pressure drop coefficient. Secondly, the migrating vapor upon condensing surfaces, settles as flowing liquid film on the tube surface. The flowing liquid is draining off as droplets and jet between adjacent tubes, and inundating subsequent tubes in the flow path. The effect of inundation on the pressure drop has been studied in literature [3]. The pressure drop coefficient ζ, of a real condenser may be expressed as the sum of the single-phase flow effect, ζ_d, the suction effect, ζ_{su}, and the inundation effect ζ_{inun}. The value of ζ_d, can be determined from literature data for single-phase flow [3,5,7].

In this study, two staggered tube arrangements are performed to evaluate experimentally the pressure drop in the presence of condensate inundation. The conventional tube arrangement with identical transverse and longitudinal pitches; $S_T = S_L = 0.030$ m and suggested staggered tube arrangement with variable pitch, the transverse pitch changes with equal steps from the first row to the last row. The two staggered tube arrangements have the same transverse pitch for the last row at flow exit. The data are presented for the pressure drop of flow across banks of tube in the Reynolds number range $10^3 \leqslant \mathrm{Re} \leqslant 35 \times 10^3$ and the inundation flow rate range $I = 0.01–0.075$ kg/m s. These values of the data represent the variation of the condensation rate over the surface of the condenser tube bank. An experimental test rig has been constructed see (Fig. 1).

The main purpose of this investigation was to study experimentally the effect of transverse pitch variation and condensate inundation on the pressure drop. The effect of the adapted value of ζ obtained experimentally for suggested tube arrangement on the condensation rate could be investigated theoretically. This value of ζ takes into considerations, the single-phase flow effect, and the inundation effect. The equations governing the conservation of mass, momentum and air mass fraction of steam condenser are solved in one-dimensional model. In addition, this investigation presents a comparison between two types of tube banks.

2. Experimental set-up

Airflow rate, together with inclusion of artificial inundation system allows simulation of the condition within the condenser tube nest. The aim of this experiment is to evaluate the pressure drop on staggered tube arrangement having different transversal and identical longitudinal pitches in the presence of condensate. The test rig, Fig. 1 is a modified version of that described by Abd El-Kariem [3]. The test set-up is composed of three parts: test section, air circulating system and water circulating system as shown in Fig. 1. Air was supplied from a fan with a power of 15 kW. Air leaving the blower was passes through a pipe of 101.5 mm diameter and 4200 mm length. The air leaving the pipe passes through expansion chamber (diffuser duct) with 10° divergence angle and 1850 mm length. To attain steady state uniform flow at the inlet of the test section, 1 m length rectangular duct was used as