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ScienceDirect
International Journal of Heat and Mass Transfer 50 (2007) 1288–1294
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Experimental research of highly viscous fluid cooling in cross-flow to a tube bundle

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Received 14 September 2005; received in revised form 17 July 2006
Available online 30 November 2006

Abstract

The paper deals with the results obtained during experimental research of the heat transfer performances of cross-flow heat exchanger with highly viscous fuel oil flowing normal to the tube bundle with $Re < 1$ and $Pr \sim 2000$. Experimental research was performed on the oil cooler that consist of 50 in-line, with 10 mm outside tube diameter, 100 mm tube length, with both longitudinal and transversal tube pitch of 19.5 mm. Comparison of experimental results with equations from literature sources showed that dispersion of measured and calculated values is significant. In order to obtain more accurate equation statistical analysis was performed and dimensionless equation in the form

$$Nu_D = 3.17 \cdot Re_{Dc}^{0.1} \cdot Pr^{1/3} \cdot \left(\frac{Pr}{Pr_w}\right)^{0.25}$$

is obtained. Similar form of equation can be obtained when Reynolds–Colburn analogy is applied on previous experimental research of pressure drop.

Keywords: Tube bundle; Cross-flow; Heat transfer; Highly viscous fluid; Laminar flow

1. Introduction

Shell-and-tube heat exchangers and double-pipe heat exchangers are commonly used for heating or cooling of highly viscous fluids, such as fuel oils. Cross-flow heat exchangers can also be used for same purposes, with viscous fluid flowing normal to a tube bundle. The problem of cooling of highly viscous fluid flowing outside tube bundle is treated in few open literature sources, especially in case of low Reynolds and high Prandtl numbers.

In order to further investigate the problem we have built experimental setup with two cross-flow heat exchangers, presented in Fig. 1. The main elements of experimental setup are: storage tank (pos. 1), pump (3), cross-flow heat exchanger – heater (4), cross-flow heat exchanger – cooler (5) and atmospheric steam boiler (7). Process fluid (water and highly viscous heating oil) was heated by saturated steam at atmospheric pressure in heat exchanger 4, and than cooled by cold tap water in heat exchanger 5. Electric boiler (6 kW) was used for steam production. Steam condensed in exchanger 4 and condensate returned to boiler, passing through reservoir (6) with steam trap (11). Additional cooling of process fluid was done in the storage tank by pipe coil in order to achieve more stationary conditions. Test heat exchanger was cooler. Flow rates were controlled by valves (2, 8, 9 and 10). Process fluid flow rate was varied from 0.036 kg/s to 0.847 kg/s. Cold water flow rate was in order 0.59–0.84 kg/s providing laminar and transition flow in tubes.

Both heater and cooler consist of 50 vertical bare cooper tubes, with $D/d = 10/8$ mm tube diameter. The tube

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doi:10.1016/j.ijheatmasstransfer.2006.09.004

Nomenclature

a, a_1, a_2 parameters
c_p specific heat capacity at constant pressure J/(kg K)
c_r correction factor for the number of tube rows
d inner diameter of tube (m)
D outer diameter of tube (m)
f_A arrangement factor
k overall heat transfer coefficient (W/(m^2 K))
L characteristic length (m)
LMTD logarithmic mean temperature difference (°C)
$\dot{m}$ mass flow rate (kg/s)
MTD real mean temperature difference (°C)
n number of experimental runs
N number of tube rows
NTU number of transfer units
Nu_D Nusselt number calculated using characteristic length D
Nu_L Nusselt number calculated using characteristic length L
P heat efficiency parameter $P = \frac{t_{2o} - t_{2i}}{t_{1i} - t_{2i}}$
Pr Prandtl number $Pr = \frac{c_p \cdot \mu}{\lambda}$
$\dot{Q}$, W heat duty
R ratio of heat equivalents $R = \frac{t_{1i} - t_{1o}}{t_{2o} - t_{2i}}$
Re_D Reynolds number calculated using characteristic length D and velocity in minimal cross-section
Re_{Dc} Reynolds number calculated using characteristic length D and velocity in empty channel
Re_L Reynolds number calculated using characteristic length L and velocity in minimal cross-section
s tube pitch (m)
S heat transfer surface calculated for outside tube diameter (m^2)
t temperature (°C)
w fluid velocity (m/s)
z_i measured value of parameter z in the ith experimental run
z_i^c correlated value of parameter z in the ith experimental run
z_{av} average value of parameter z for the complete set of the experimental data $z_{av} = \frac{\sum_{i=1}^{n} z_i}{n}$

Greek symbols
α heat transfer coefficient (W/(m^2 K))
Δ_{av} standard deviation $\Delta_{av} = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{z_i - z_i^c}{z_i}\right)^2}{n}}$
Δm_1 uncertainty of mass flow rate measurement (kg/s)
Δt uncertainty of temperature measurement, characteristic temperature difference (°C)
Δ_{st} unsteadiness of working regime
ε correction factor for mean temperature difference
λ thermal conductivity (W/(m K))
μ dynamic viscosity (Pa s)
ν kinematic viscosity (m^2/s)
ρ density (kg/m^3)
ξ friction factor (loss coefficient) in Darcy–Weisbach form of pressure drop equation

Subscripts and superscripts
1 hot
2 cold
av average
c channel
i inlet/inside
l longitudinal
lam laminar
m mean
max maximal
min minimal
o outlet/outside
t transversal
tur turbulent
w wall

arrangement is in-line with $s_l = s_t = 19.5$ mm longitudinal and transversal pitch, placed in 100×100 mm channel. Heat exchangers contain $N = 10$ tube rows each with 5 tubes in a row. Viscous fluid used in experiment was heavy fuel oil with the following properties in temperature range from 25 °C to 100 °C

$$\rho = 976 - 0.677 \cdot t, \ \mathrm{kg/m^3} \tag{1}$$

$$c_p = 1644 + 3.84 \cdot t, \ \mathrm{J/(kg\,K)} \tag{2}$$

$$\lambda = 0.075 \ \mathrm{W/(m\,K)} \tag{3}$$

$$\nu = 1.71 \times 10^{-6} \cdot \exp\left(\frac{223.6}{t}\right), \ \mathrm{m^2/s} \tag{4}$$

where t is fluid temperature in °C.

All temperatures were measured with calibrated laboratory thermometers with 0.1 °C accuracy. Temperatures of process fluid were kept in range 24–62 °C corresponding to Prandtl numbers from 4.7 (minimal value for water) to 2315 (maximal value for oil). Fluid flow rates of process fluid and cold water were measured by volume–time measurement method.

2. The calculation of experimentally obtained heat transfer coefficient

Three heat duties can be calculated from each set of test data for cooler: