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SHORTER COMMUNICATIONS

HEAT TRANSFER THROUGH COILED TUBES IN AGITATED VESSELS

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NOMENCLATURE

B_n,	number of baffles in the vessel;
C,	a constant factor in equation (2);
C_p,	specific heat of the vessel liquid;
D_a,	diameter of the agitator;
D_c,	mean diameter of the helical coil;
D_t,	inside diameter of the tank;
d_i,	inside diameter of the tube of the coil;
d_m,	mean diameter of the tube of the coil;
d_o,	outside diameter of the tube of the coil;
H_a,	depth of the agitator;
h_i,	inside coil film heat-transfer coefficient;
h_o,	outside coil film heat-transfer coefficient;
K,	thermal conductivity of the vessel liquid;
k_m,	thermal conductivity of the metal of the coiled tube;
N,	agitator speed;
U_o,	overall heat-transfer coefficient based on outside diameter of coil-tube;
V_i,	mean velocity of liquid in the coil;
X_ω,	thickness of the metal wall of the coil tube.

Greek symbols

β,	$h_{i(\text{coil})}/h_{i(\text{st. tube})}$;
ρ,	density of vessel liquid;
μ,	viscosity of the vessel liquid at the bulk temperature;
μ_ω,	viscosity of the vessel liquid at the wall temperature.

INTRODUCTION

THE RATE of heat transfer to or from an agitated liquid in a vessel is a function of the physical properties of the agitated liquid, and of the heating or cooling medium, of the vessel geometry, and of the degree of agitation. The earlier work in the field of jacket and coil-side heat transfer in agitated vessels was reviewed recently by Nooruddin and Rao [1], who have proposed the following correlation for the outside film heat-transfer coefficient h_o of a helical coil as a function of vessel liquid properties, and of geometric and operating characteristics of the turbine agitator.

$$\frac{h_o D_t}{K} = 1{\cdot}04 \left(\frac{D_a^2 N \rho}{\mu}\right)^{0{\cdot}67} \left(\frac{C_p \mu}{K}\right)^{0{\cdot}33} \left(\frac{D_a}{D_t}\right)^{0{\cdot}18} \times \left(\frac{B_n}{6}\right)^{0{\cdot}28} \left(\frac{\mu}{\mu_\omega}\right)^{0{\cdot}14} \tag{1}$$

The aim of the present investigation was to study the effect of the dimensions of the helical coil on the outside-film and inside-film heat-transfer coefficients, and also the effect of the location of the agitator within the vessel. The parameters studied with 5 different coils were coil-tube diameter [(i) $d_o = 1{\cdot}91$ cm, $d_i = 1{\cdot}27$ cm, (ii) $d_o = 1{\cdot}27$ cm, $d_i = 0{\cdot}953$ cm, (iii) $d_o = 0{\cdot}96$ cm, $d_i = 0{\cdot}635$ cm] mean helix diameter of the coil [(i) 24·8 cm, (ii) 20·4 cm, (iii) 15·8 cm, (iv) 24·1 cm], speed of agitation (202–603 rev/min), and depth of the agitator in the vessel ($H_a = 9{\cdot}5$ cm, 11·8 cm, 16·8 cm, and 22·3 cm).

EXPERIMENTAL WORK

The experimental set-up in the present studies was the same as that used by Nooruddin and Rao [1], and the transfer of heat was carried out from continuously flowing hot water inside the vessel to cooling water flowing inside the helical coil.

The copper cylindrical vessel, of 35·6-cm i.d. (D_t) and 50-cm high, has a flat bottom, and is equipped with a 4-flat blade turbine agitator of 11·8-cm diameter (D_a). The turbine agitator was driven by a 2-hp variable-speed drive motor through a gear-reduction unit. Two baffles of width 3·0 cm were installed radially at the wall of the vessel at 180° apart. The vessel was lagged thermally and mercury-in-glass thermometers of 0·1 degC accuracy were used to measure the inlet and outlet temperatures of the hot (tank) liquid, and of the cooling water (coil liquid).

The hot water from the hot liquid tank was transported to the vessel by a centrifugal pump through a calibrated Rotameter and a heat exchanger, and the rate of heat input to the hot liquid tank was controlled with the aid of dimmerstats on the immersion heaters, with a view to obtaining a constant temperature of 50°C (±0·5 degC) for the agitated liquid in the vessel. The vessel liquid flow rate was kept constant at 323 kg/h. The cold water was also transported by a pump, to the coil through a calibrated Rotameter and its flow rate was varied from about 129 to 1509 kg/h, the lower limits of flow with each of the 5 coils used, being so selected as to ensure fully developed turbulent flow inside the coil. The speed of the agitator was measured by a tachometer. At steady-state conditions, observations were made of the flow rate, temperatures and speed of agitator for any run. A total of about 90 runs were taken in the present investigation.

The overall heat-transfer coefficients, U_o were calculated from the rate of heat gain by the coil liquid, and thereafter the individual film coefficients h_o and h_i of the coil were evaluated from the Wilson plots ($1/U_o$ versus $1/V_i^{0\cdot8}$) by way of the equation

$$\frac{1}{U_o} = \left(\frac{d_o}{\beta \,.\, C \,.\, d_i}\right)\frac{1}{V_i^{0\cdot8}} + \left(\frac{1}{h_o} + \frac{d_o}{d_m}\cdot\frac{X_\omega}{k_m}\right). \qquad (2)$$

The Wilson plot gives a straight line, when h_o is maintained constant by keeping the flow rate and temperature of the agitated liquid constant and using constant speed of agitation. The value of β, which is $h_{i(\text{coil})}/h_{i(\text{st. tube})}$, was evaluated for each coil.

RESULTS AND DISCUSSION

It was found that the thermal resistance of the outside film of the coil was considerably decreased with increase in speed of agitation from 200 to 500 rev/min, and that further increase of speed above 500 rev/min did not appear to have any significant effect, thereby indicating that h_o increased with agitator speed up to about 500 rev/min.

Depth of the agitator (H_a)

Using helical coil of d_i = 1·27 cm, d_o = 1·91 cm and D_c = 24·8 cm, the depth of impeller was varied over the range 9·5 cm–22·3 cm, corresponding to the ratio H_a/D_t of 0·267–0·627, while the depth corresponding to the standard configuration was 11·8 cm (H_a/D_t = 0·33). In Fig. 1, Nusselt number $(h_oD_t)/K$ was shown against H_a/D_t on logarithmic co-ordinates, and it was observed to vary with a power of 0·14 for H_a/D_t. This value of 0·14 agreed closely with the value of 0·12 reported by Strek [2] from his heat-transfer results in baffled, jacketed, agitated vessels. Chapman, Dallenbach and Holland [3] have, however, found this power of H_a/D_t to be 0·4, and this higher value was attributed by the authors to their using a lower range of 0·083–0·33 for H_a/D_t.

Coil-tube diameter

Over the range of 0·0268–0·0537 of the ratio, d_o/D_t studied in the present work, it was noted from Fig. 2 that the coil outside film heat-transfer coefficients, h_o evaluated as h_oD_t/K showed a variation with a −0·48 power of d_o/D_t. This value of −0·48 is in good agreement with −0·50 of Oldshue and Gretton [4], who used combination helical coils having alternate turns for heating and cooling, and turbine agitators. The value reported by Pratt [5] for this exponent of d_o was −0·30, the difference is probably due to Pratt's use of paddle agitators.

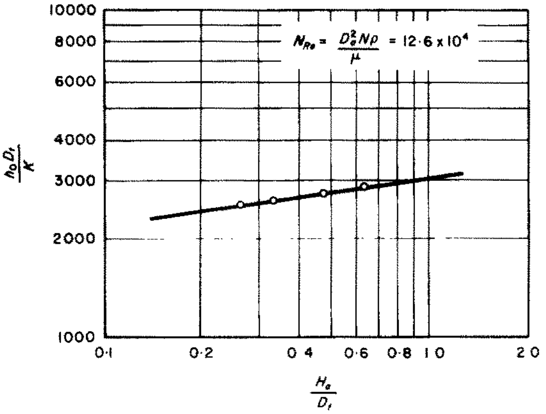

FIG. 1.

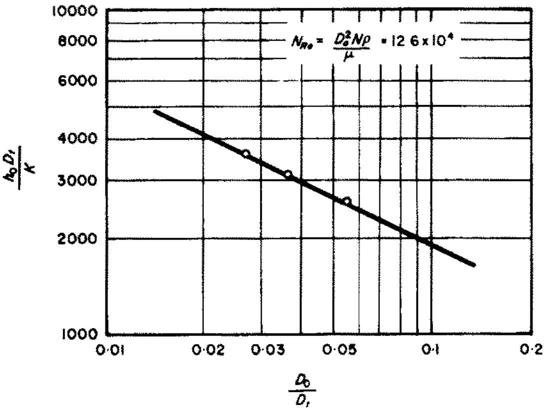

FIG. 2.

Mean diameter of the coil (D_c)

From Fig. 3, it was observed that (h_oD_t/K) varied with a power of −0·27 of D_c/D_t over the range of this ratio from 0·444 to 0·697. The only published work available for comparison is that of Pratt [5], who has found this power to be −0·25, while working with paddle agitators.

Agitator Reynolds number

By graphical treatment of experimental results, it was found that Nusselt number (h_oD_t/K) varied with 0·67 power of the agitator Reynolds number ($D_a^2 N\rho/\mu$) up to a value of $2{\cdot}1 \times 10^5$ of this number, corresponding to a speed of 500 rev/min. This value of 0·67 agreed with the same value reported recently by Oldshue and Gretton [4], and Nooruddin and Rao [1] for turbine agitation in agitated vessels.

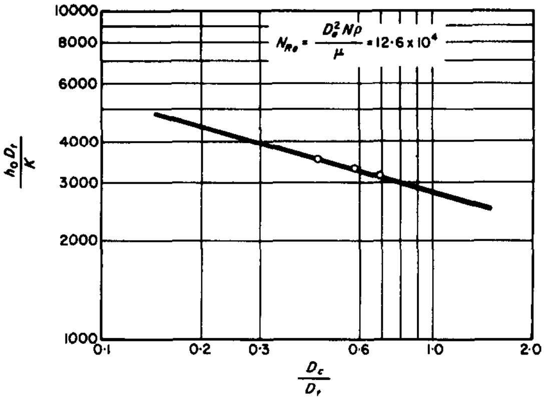

FIG. 3.

CORRELATION

The effect of Prandtl number ($C_p\mu/K$) has been studied by Nooruddin and Rao [1] who found that ($h_o D_t/K$) varied with 0·33 power of $C_p\mu/K$.

The following correlation incorporating the effect of Prandtl number has been obtained from the treatment of the experimental data

$$\frac{h_o D_t}{K} = 0{\cdot}18 \left(\frac{D_a^2 N\rho}{\mu}\right)^{0\cdot67} \left(\frac{C_p\mu}{K}\right)^{0\cdot33} \left(\frac{d_o}{D_t}\right)^{-0\cdot48} \times \left(\frac{D_c}{D_t}\right)^{-0\cdot27} \left(\frac{H_a}{D_t}\right)^{0\cdot14}. \quad (3)$$

This correlation predicts our experimental results with an average deviation of 1·7 per cent and a maximum deviation of 3·8 per cent; it could be utilized to estimate, h_o, coil outside film heat-transfer coefficients, in agitated vessels, using a 4-flat blade turbine agitator for $D_a = \frac{1}{3}D_t$.

Values of β were correlated as a function of the coil curvature ratio, d_i/D_c, which was varied from 0·0264 to 0·0603 in the present work:

$$\frac{h_{i(\text{coil})}}{h_{i(\text{st. tube})}} = \beta = \left[1 + 3{\cdot}46\left(\frac{d_i}{D_c}\right)\right]. \quad (4)$$

CONCLUSIONS

For heat transfer through coiled tubes in agitated vessels, using flat-blade turbine agitator, the proposed correlation, equation (3), could estimate h_o values as a function of the geometrical parameters of helical coil and also the depth of the agitator for the standard configuration of the vessel for which $D_a = \frac{1}{3}D_t$. Further, the modified Dittus–Boelter equation with the included correction factor, β could be satisfactorily used for predicting the inside film heat-transfer coefficient, h_i, of any helical coil.

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FORCED CONVECTION BOILING INSIDE HELICALLY-COILED TUBES

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THE AUTHORS are currently conducting a study of forced convection boiling inside electrically heated, helically coiled, tubes. Some of the phenomena appear to be sufficiently unexpected and interesting to call early attention to them by this communication. A more complete presentation of results and analysis will appear later.

The incentive for this study was the possibility of achieving continuous de-entrainment of liquid droplets because of the large radial accelerations induced by the helical path. Continuous separation of phases would make production of high quality or superheated outlet vapor streams easier by eliminating the fog flow regime.

The feasibility of single pass production of superheated

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