Heat Transfer to Coils in Propeller-Agitated Vessels

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Although heat transfer in vessels fitted with coils has received considerable attention for the cases of paddle and turbine agitation, it is curious that studies of heat transfer in *propeller-agitated* vessels have been few (*1*). In fact, only one study has been mentioned in the literature, its preliminary nature being indicated by the restriction of the report to five printed lines, containing virtually no experimental details (*1*).

The experimental work in the present study was carried out in three series totaling 173 runs:

Series A—Baffle study: Baffle width and baffle number were varied for a range of agitator speeds.

Series B—Propeller study: Propeller diameter and propeller elevation above the vessel floor were varied.

Series C—Coil geometry and physical properties: Coil tubing diameter and gap between coil turns were varied, and a range of agitator speeds and four different liquids were used (water in series A and B, three oils in series C).

EQUIPMENT

The vessel was cylindrical, flat bottomed, and capable of holding 30-gal. The upthrusting three-bladed propellers were mounted on the shaft coaxially with the tank. Clean copper coils were also mounted with their axes coincident with the axis of the vessel. Water was used as the coolant. Full-length baffles were spaced radially at equiangular intervals around the vessel. Table 1 compares the equipment used in each of the three series, and Table 2 gives the properties of the oils used.

Baffle Study

The propeller shaft was driven with a 1/3-hp. single-phase a.c., variable-speed motor with a Weston Model 273 rev./min. meter to measure the impeller speed. The batch fluid was maintained at a constant temperature through a run by continuous and controlled introduction of open steam, which therefore constituted a small additional source of agitation. The steam was injected at a radial distance of 6¼ in. from the center of the vessel and 7¼ in. above the bottom. This injection point was about level with the second turn of the coil counting from the top. The horizontal plane through the propeller coincided approximately with that passing through the third, or central, turn of the coil.

Insulation was provided by glass wool packing in a 2-ft.-square box that encased the vessel.

Propeller Study

A ½-hp. single-phase a.c., single-speed Lightnin mixer was used. The shaft speed was measured with a Veeder revolution counter and stopwatch; square pitch propellers were employed. The water level was maintained at 20 in. by removing condensed steam at the end of each heating period. Insulation was provided by setting the 30-gal. tank concentrically within a 55-gal. drum and filling the annular space with ¼-in. vermiculite.

Coil Geometry

The agitator was driven by a ¾-hp. Reeves variable-speed three-phase a.c. motor.

The bulk liquid was heated (or cooled) by passing steam (or water) through the coil.

EXPERIMENTAL PROCEDURE

Baffle Study

Water was used as the agitated liquid for these *steady state* runs. In the first set of seventy-five runs the effects of using two, three, four, five, and six baffles, all 2 in. wide, were investigated over the range of Reynolds numbers from 6.42×10^4 to 8.2×10^5. Four baffles were used throughout the second set of forty-five runs with widths of 1, 2, 2½, and 3 in. Reynolds numbers ranged from 6.53×10^4 to 8.21×10^5. Shaft speeds ranged from 100 to 1,200 rev./min. throughout.

At the beginning of each run the vessel was filled with water to a depth of 20 in., and the steam valve opened to raise and hold the temperature of the water at 120°F. The flow rate through the coil was

TABLE 1. EQUIPMENT USED IN SERIES A, B, AND C

	A	*B*	*C*
Outside diameter of coil helix, in.	10	13	13
Coil tubing diameters, in. O.D.	¾ (16 B.W.G.)	¾ (20 B.W.G.)	¾, ½, ¼ (20 B.W.G.)
Number of coil turns	5	7.5	7.5
Spacing between adjacent turns, in.	0.92	1¼	1¼, 1⅞, 2
Propeller diameter, in.	6	3, 6, 9	6
Vessel diameter, in.	18	18¼	18¼
Liquid height, in.	20	20	19¼, 20
Propeller height above bottom, in.	6½	3, 6, 9, 12, 15	6
Propeller pitch, in.	8	3, 6, 9	6
Heat transfer surface, sq. ft.	2.57	5.13	5.13, 3.43, 1.71
Baffle numbers	2, 3, 4, 5, 6	4	4
Baffle widths, in.	1, 2, 2½, 3	1⅞	1⅞
Baffle length, in.	24	24	24
Liquids used	Water	Water	Oil: A.P.I. 29.2 A.P.I. 28 A.P.I. 26.2
Drum material	Aluminum	Aluminum	Steel
No. of runs	120	22	31

INFORMATION RETRIEVAL

(Continued from page 950)

Adsorption kinetics in fixed beds with nonlinear equilibrium relationships, Tien, Chi, and George Thodos, **A.I.Ch.E. Journal, 11,** No. 5, p. 845 (September 1965).

Key Words: A: Kinetics-8, Adsorption-8, Fixed Beds-9, Mass Transfer-8, Nonlinear Equilibrium Relationship-9, Bed Length-6, Time-6, Concentration-7, Breakthrough Curve-8, Ion Exchange-8.

Abstract: Previous work on ion exchange kinetics for systems having nonlinear equilibrium relationships has been extended by means of computer studies conducted to produce additional concentration-bed-length-time relationships. The results are represented graphically.

Forced convection mass transfer: Part II. Effect of wires located near the edge of the laminar boundary layer on the rate of forced convection from a flat plate, Thomas, David G., **A.I.Ch.E. Journal, 11,** No. 5, p. 848 (September, 1965).

Key Words: A. Convection-8, 7, Forced-0, Mass Transfer-8, 7, Wires-6, 9, Cylinders-6, 9, Promoters-6, Turbulence-9, Velocity-6, Spacing-6, Boundary Layers-9, Laminar-0, Naphthalene-5, Hydrocarbons-5, Air-5, Wind Tunnel-10.

Abstract: The local and the average rates of forced convection through laminar boundary layers on a flat plate were shown to be markedly increased by locating small cylinders near the outer edge of the boundary layer. The local rate of forced convection was strongly peaked directly beneath each cylinder; the magnitude of the effect depended upon the free stream velocity, the spacing between cylinders, and the gap between the cylinders and the plate.

An eddy viscosity model for friction in gas-solids flow, Julian, F. M., and A. E. Dukler, **A.I.Ch.E. Journal, 11,** No. 5, p. 853 (September, 1965).

Key Words: A. Prediction-8, Velocity Distribution-8, 9, Eddy Viscosity-8, 9, Gas-Solid Flow-8, 9, Equations-10, Pressure Drop-7, 9, Calculation-8, Friction Factor-10, Two-Phase-0, Pipe-9, Loading-6, Solids-9, Fluid Flow-8, Turbulent Flow-8, Dispersed Flow-8, Velocity Distribution-7.

Abstract: The equations normally used to predict velocity distribution and eddy viscosity in single-phase flow systems can be adapted to fit gas-solids flow systems by including a term to account for the quantity of solid matter carried by the gas stream. This solids loading is expressed as pounds of solid per pound of gas. These modified equations can then be used to calculate the pressure drop of a solids-laden gas stream flowing in a pipe by means of a two-phase friction factor. Comparison of this approach with available pressure drop data is used to check its validity and to evaluate the constants in the equations.

Suction nucleate boiling of water, Wayner, P. C., Jr., and A. S. Kesten, **A.I.Ch.E. Journal, 11,** No. 5, p. 858 (September, 1965).

Key Words: A. Suction Nucleate Boiling-8, Heat Transfer-8,7, Interfacial Tension-8, Evaporative Cooling-8, Polytetrafluoroethylene-6, 10, Heat Exchanger-4, Nucleation-6, Heat Flux-6, Pressure Drop-6, Temperature-7, Surface-9, Heat Transfer Coefficient-7, Water-1, Steam-2, Heater-10, Porous-0, Copper-10, Pores-6.

Abstract: Suction nucleate boiling was investigated experimentally and theoretically. The experimental results demonstrated that: (1) interfacial free energy can be used to direct the flow of liquid and vapor in a desired direction and to separate vapor from liquid at the point of vapor generation; (2) the heat transfer coefficient for suction nucleate boiling is higher than that associated with normal boiling; and (3) a porous heat exchanger can be designed to give stable transition from nucleate boiling into film boiling. The theoretical analysis, which was based on experimental observations, indicated that extremely high heat fluxes and heat transfer coefficients are possible with small pores. Comparison of the experimental and theoretical results demonstrated that the full potential of suction nucleate boiling was not attained in the experiments and indicated some of the experimental refinements needed to attain this potential.

(Continued on page 954)

determined by collecting and weighing the discharge in a measured time interval. The coil inlet and outlet temperatures and the bulk water temperature were measured with mercury-in-glass thermometers calibrated to 1/10°F.; all temperatures were measured at steady state conditions. A continuous trickle of water overflowed from the tank to compensate for the condensing steam and to maintain the bulk temperature at 120°F. and the liquid depth at 20 in.

Propeller Study

These data were taken for *unsteady state* conditions. The rotational speed of the agitator and the run time were recorded for each run. At the beginning and end of each run the inlet and outlet coil temperatures and vessel temperature were measured with mercury-in-glass thermometers calibrated to 1/10°F. The coolant flow rate was measured with a rotameter.

Coil Geometry

In this program, again for *unsteady state* conditions, oils of three different A.P.I. gravities were used as the agitated liquid. The oil was heated by injecting high-pressure steam into the coil until the oil temperature was about 40°F. above the value at which the oil viscosity would be too high to afford fully turbulent flow at the selected agitator speed. The temperature of the oil was next lowered 10°F. and then a further 20°F. for data recording. The agitator speeds were 600, 800, and 1,000 rev./min. Each of the three coils was used with each of the three oils for the agitator speeds mentioned above.

Agitated liquid properties were evaluated at the average vessel temperature (8) and coolant properties at the average coolant temperature in all runs.

Calculation of h_c

The overall coefficient U_o was calculated from the following equation (9) for the steady state runs of series A.

$$\frac{dQ}{d\theta} = w_c\, c_{pc}\,(t_c - t_{ca}) = U_o A \, \frac{t_c - t_{ca}}{\ln \dfrac{t_h - t_{ca}}{t_h - t_c}}$$

and from the equation below (9) for the unsteady state runs of series B and C.

$$\ln \frac{t_{ha} - t_{ca}}{t_{hb} - t_{ca}} = \frac{w_c\, C_{pc}}{m c_p}\left(1 - \frac{1}{K}\right)\theta_t$$

where $K = \exp\,(U_o A / w_c c_{p_c})$

The individual coefficient for the water inside the coil h_i, was calculated in all cases by the following expression (5):

$$h_i = 0.023\,\frac{k_c}{d_i}\left(\frac{d_i\, V_c\, \rho_c}{\mu_c}\right)^{0.8} \left(\frac{c_{pc}\,\mu_c}{k_c}\right)^{0.4}\left(1 + 3.5\,\frac{d_i}{d_c}\right)$$

TABLE 2. MINERAL OIL PROPERTIES FOR SERIES C

Oil	Specific gravity	Viscosity centipoises 26°C.	37.8°C.	89°C.	99°C.
A.P.I. = 26.2	0.897		263		18.3
A.P.I. = 28	0.887	195		15	
A.P.I. = 29.9	0.880		69.1		7.76

Other properties: reference 8.

Knowing the wall thickness of the clean copper tubing permitted evaluation of the individual agitated-side coefficient h_c from the relationship (*10*)

$$\frac{1}{U_o} = \frac{d_o}{d_i h_i} + \frac{x_w}{k_m}\frac{d_o}{d_{lm}} + \frac{1}{h_c}$$

The term μ_w was estimated as on page 444 of reference 9.

RESULTS

The data from all three series for both steady and unsteady state heat transfer (totaling one hundred and seventy-three runs) are available* and were correlated by a least squares procedure on an I.B.M. 1620 digital computer as follows

$$\frac{h_c d_o}{k} = 0.0573\left(\frac{L^2 N\rho}{\mu}\right)^{0.67}\left(\frac{c_p\mu}{k}\right)^{0.41}\left(\frac{\mu}{\mu_w}\right)^{0.034}\left(\frac{H}{D}\right)^{-0.254}\left(\frac{P}{L}\right)^{2.33}(N_b)^{-0.077}\left(\frac{W}{D}\right)^{-0.058}\left(\frac{d_c}{D}\right)^{0.572}\left(\frac{d_g}{d_o}\right)^{-0.018}$$

for $1.3 \times 10^4 \leqq L^2N\rho/\mu \leqq 1.1 \times 10^6$. The multiple correlation coefficient for this relationship was 0.894. Observed Nusselt numbers vs. those calculated from the above correlation are plotted in Figure 1. The few data points showing some scatter at calculated Nusselt numbers above about 250 all correspond to the data for water as the agitated fluid when the highest shaft speeds and the lowest numbers of baffles are used. These conditions were the most conducive to a certain amount of aeration of the agitated water, which would be expected to introduce deviations in the data. This explanation is precisely that invoked by Cummings and West (*6*) to explain why in *turbine* agitation of six different liquids their most inconsistent heat transfer results were obtained with water at the highest impeller speeds in an unbaffled vessel.

The exponents obtained on the Reynolds and Prandtl numbers and on the group d_c/D are virtually the same as those found by Oldshue and Gretton (*11*) for the case of heat transfer to coils in a vessel agitated by single turbines with six flat blades. The directional effects of the quantities N_b, W, and d_g are all consistent with the expected result of decreasing the fluid velocity past the heat transfer surface as these variables increase.

The ratio μ/μ_w is usually employed to reconcile data from both heating and cooling runs. Thus Pratt (*12*) found it unnecessary to introduce μ/μ_w when correlating results confined to cooling, as in the present work. Even when correlating both heating and cooling data, Oldshue and Gretton (*11*) found the exponent on μ/μ_w to vary widely and in a complex manner with μ, μ/μ_w, and with type of tube for coils with turbine agitation. The often-used (*1*) exponent of 0.14 on μ/μ_w was introduced by Chilton, Drew, and Jebens (*4*); however, Chapman and Holland (*3*) point out, "The viscosity ratio exponent [of Chilton et al.] was not determined but was taken from the work of Sieder and Tate (12) (for tubes)." Others have since made this assumption about the arbitrary adoption of the exponent 0.14 (*2, 6, 14*). Now in a careful, recent study on heat transfer to fluids in tubes, Malina and Sparrow (*7*) state, "... the Seider-Tate correction $[(\mu/\mu_w)^{0.14}]$ over-predicts the variable property effects. . .it would appear that $(\mu/\mu_w)^{0.05}$ serves as an adequate correction factor." Evidently these more recent findings lend support to the relatively low exponent on μ/μ_w found in the present work.

* Tabular material has been deposited as document 8475 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for \$2.50 for photoprints or \$1.75 for 35-mm. microfilm.

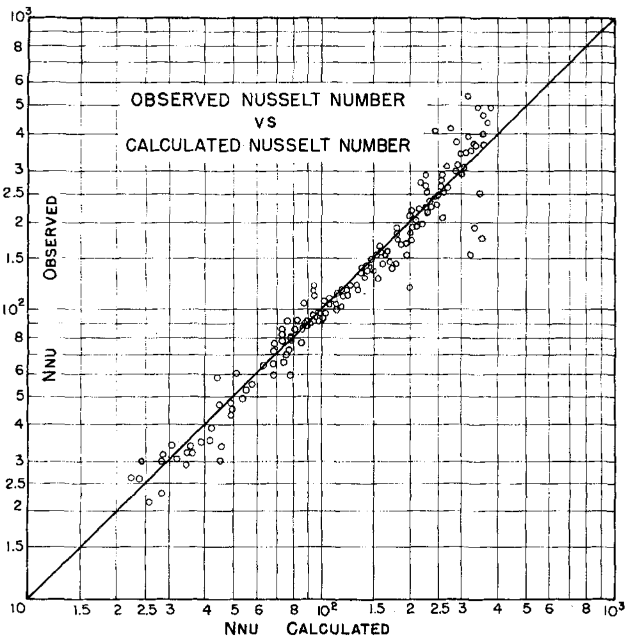

Fig. 1

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NOTATION

- A = outside area of coil tube, sq. ft.
- c_p = specific heat of agitated liquid, B.t.u./(lb.) (°F.)
- c_{pc} = specific heat of cooling liquid, B.t.u./(lb.) (°F).
- D = vessel diameter, ft.
- d_c = diameter of the coil helix, ft.
- d_g = gap between coil turns, ft.
- d_i = inner diameter of coil tubing, ft.
- d_{lm} = logarithmic mean diameter of coil tubing, ft.
- H = height of propeller above vessel floor, ft.
- h_c = individual agitated-side coefficient of heat transfer for coils, B.t.u./(hr.) (sq. ft.) (°F.)
- h_i = individual coefficient of heat transfer inside coil tubing, B.t.u./(hr.) (sq. ft.) (°F.)
- k, k_c = thermal conductivity of agitated liquid and of the cooling liquid, respectively, B.t.u./(hr.) (ft.) (°F.)
- k_m = thermal conductivity of coil tube wall, B.t.u./(hr.) (ft.) (°F.)

(Continued from page 952)

Gas-liquid mass transfer in cocurrent froth flow, Heuss, J. M., C. J. King, and C. R. Wilke, **A.I.Ch.E. Journal, 11,** No. 5, p. 866 (September, 1965).

Keywords: A. Two-Phase Flow-8, 10, Froth Flow-8, 10, Bubble Flow-8, 10, Cocurrent Contacting-4, 10, Mass Transfer-4, 8, Absorption-7, 8, Water-5, Air-5, Ammonia-1, Oxygen-1, Polarography-10, Conductivity-10, Bubbles-8, 9, Size-7, Flow Rate-6, Temperature-6.

Abstract: The absorption of ammonia and oxygen in horizontal cocurrent gas-liquid froth flow in a 1-in. I.D. pipe has been investigated. At superficial liquid rates between 2×10^6 and 3.2×10^6 lb/hr.-sq.ft. and superficial gas rates between 5×10^3 and 18×10^3 lb./hr.-sq.ft. the length of a transfer unit in both systems was between 0.5 and 4.0 ft. The effects of distance and temperature were also investigated.

Effects of mixing on chain reactions in isothermal photoreactors, Hill, Frank B., and Richard M. Felder, **A.I.Ch.E. Journal, 11,** No. 5, p. 873 (September, 1965).

Key Words: A. Mixing-6, Diffusion-6, Conversion-7, Quantum Yield-7, Photoreactors-9, Isothermal-0, Radiation Attenuation-6, Chemical Kinetics-7, Design-8, Performance-7, Ultraviolet Light-10, Ionizing Radiation-10, Geometry-6, Mode of Chain Termination-6.

Abstract: An analytical study of the interaction of mixing, radiation attenuation, and chemical kinetics in isothermal photoreactors is presented. For a particular chain reaction mechanism in the presence of stationary state kinetics and low conversion, the conditions required for the existence of mixing effects are formally stated and the direction of change of conversion and quantum yield resulting from the introduction of mixing are established. Calculated results are presented for monoenergetic, unidirectional sources. Factors considered include mode of chain termination, radiation attenuation law, photoreactor geometry, state of mixing, and reactor optical thickness. Chemical and mixing time scale considerations are discussed.

Phase equilibria for strongly nonideal liquid mixtures at low temperatures, Eckert, C. A., and J. M. Prausnitz, **A.I.Ch.E. Journal, 11,** No. 5, p. 886 (September, 1965).

Key Words: A. Vapor-Liquid Equilibria-8, Vapor-Liquid-Liquid Equilibria-8, Phase Equilibria-8, Fluids-9, Mixtures-9, Nonideal-0, Low Temperature-9, Cryogenics-8, Critical Solution Temperatures-9. B. Vapor-Liquid Equilibria-8, Hydrocarbons-9. C. Vapor-Liquid Equilibria-8, Phase Equilibria-8, Nitrogen-9, Carbon Tetrafluoride-9.

Abstract: Investigation of the nonideal behavior of mixtures of simples molecules is an important step toward improved understanding of the theory of solutions. This work describes an equilibrium apparatus suitable for the measurement of vapor-liquid and vapor-liquid-liquid equilibria of simple fluid mixtures at cryogenic temperatures. Vapor-liquid data are reported for the argon-ethane and nitrogen-carbon tetrafluoride systems.

(Continued on page 956)

L = propeller diameter, ft.
m = mass of agitated liquid, lb.$_m$
N = rotational speed, rev./hr.
N_b = number of baffles
P = propeller pitch, ft.
Q = heat flow, B.t.u.
t_c = variable temperature of cooling liquid, °F.
t_{ca} = inlet temperature of cooling liquid, °F.
t_h = temperature of hot liquid, °F.
t_{ha}, t_{hb} = initial and final temperature of hot liquid, °F.
U_o = overall coefficient of heat transfer based on A, B.t.u./(hr.) (sq. ft.) (°F.)
V_c = mean linear velocity of cooling liquid, ft./hr.
W = baffle width, ft.
w_c = mass flow rate of cooling liquid, lb.$_m$/hr.
x_w = thickness of coil tube wall, ft.

Greek Letters

θ = time, hr.
θ_t = time required to cool, hr.
μ, μ_c = viscosity at bulk temperature of the agitated liquid and the cooling liquid, respectively, lb.$_m$/(ft.) (hr.)
μ_w = viscosity of agitated liquid at coil surface temperature, lb.$_m$/(ft.) (hr.)
ρ, ρ_c = density of agitated liquid and cooling liquid respectively, lb.$_m$/cu. ft.

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