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Assembly of a Thin-Falling-Film Exchanger for Laboratory Demonstrations: Calculation of the Individual Heat-Transfer Coefficient

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Abstract: Thin-film exchangers have a large heat-transfer area per unit liquid volume that make them very efficient for industrial use. Unfortunately, they are usually less applied for education purposes. In this work, a simple experimental device with a fluid flowing as a falling film has been assembled. In addition, an experimental guide allows students to determine the individual heat-transfer coefficient in the exchanger.

The experimental setup consists of two pipes bundled as a shell-and-tube heat exchanger. The cold liquid flows in the form of a thin film that runs down inside the inner tube; the hot liquid flows down concurrently in the external one.

In order to test the operation of the device, experimental results are given for a simple test with water. Heat-transfer coefficients are calculated and a theoretical correlation obtained from the literature is compared with the experimental results. In addition, a fit of the data allows for the formulation of a new empirical equation for the transient regime.

Introduction

Nearly every plant operation in chemical engineering requires heat production or absorption. Heat may be transmitted in three ways: conduction, convection, and radiation. In the first two operations, the heat flow is proportional to ΔT, the temperature change, and in the latter to $T_1^4 - T_2^4$.

There have been many different designs for heat exchangers developed for industrial use over the years. In simple devices, both hot and cold fluids are directly mixed; however, the most widely used designs are exchangers where both fluids are separated by a wall. The usual values of the heat-transfer coefficient, *h*, for different systems are summarised in Table 1. Among them, thin-film exchangers have a large heat-transfer coefficient. This type of exchanger consists of one tube or a number of tubes bundled as in a shell and tube exchanger [1–3]. In another design [4], two large pipes form an annular clearance.

Thin-film exchangers have a large heat-transfer area per unit liquid volume. If the Reynolds number, *Re*, for the film is defined as a function of the mass flow, *m*, and the equivalent diameter, D_e, then

$$Re = \frac{GD_e}{\mu} = \frac{m}{S}\left(4\frac{S}{Z}\right)\frac{1}{\mu} = \frac{4m}{Z\mu} \qquad (1)$$

with

$$D_e = 4\frac{S}{Z} = 4\frac{(D-e)e}{D} \qquad (2)$$

where *Z* is the wet perimeter, *G* is the mass-flow velocity, *S* is the column section, *e* is the film thickness, *D* is the column diameter, and μ is the fluid viscosity. For a given mass flow, the Reynolds number does not depend on whether or not the liquid is completely filling the tube. The heat-transfer coefficient varies with the equivalent diameter as follows.

$$\frac{h_{\text{full}}}{h_{\text{film}}} = \frac{\left(\frac{4S}{Z}\right)_{\text{full}}}{\left(\frac{4S}{Z}\right)_{\text{film}}} = \frac{\dfrac{4(\pi/4)(D^2-d^2)}{\pi D}}{\dfrac{4(\pi/4)(D^2)}{\pi D}} = \qquad (3)$$
$$\frac{(D^2-(D-2d)^2)}{D^2} = 4\frac{(D-e)e}{D^2} < 1$$

where *d* is the column diameter not filled by the fluid film, the subscript full refers to the value when the whole tube is filled with the fluid, and the subscript film refers to the value when fluid is flowing down the tube as a film and not filling the tube.

Because the film thickness is always less than *D*/2, it can be deduced that $h_{\text{full}} < h_{\text{film}}$, and the flow in the form of a thin film favors heat exchange, yielding larger coefficients.

The main characteristics of these heat-exchanger devices are: low contact time, low pressure drop, high heat-flow density, and easy cleaning. The main inconvenience is that high flow rates induce waves in the falling liquid and the film can be broken, decreasing heat transfer. To avoid this problem, we can use a smaller tube and ensure its perfect verticality [5]. A compilation and comparison of literature data on heat transfer for liquid films is given by Yüksel [6].

Usually, students finishing their undergraduate chemical engineering degree have only had experience with standard heat exchangers. Large heat-transfer coefficients in film exchangers, however, makes them useful in a great number of industrial applications, like highly exothermic reactions,

Table 1. Values for the Heat Exchange Coefficients in Several Systems. (W m^{-2} K^{-1} ≅ 0.86 kcal hm^{-2} °C^{-1})

SYSTEM	*h* (W m^{-2} K^{-1})
Free convection	5–50
Forced convection with air	20–400
Fluidized bed (wall-bed)	100–600
Forced convection with water	200–10000
Boiling water	1000–40000
Thin film	*5000–20000*
Condensing water-vapor droplets	10,000–100,000

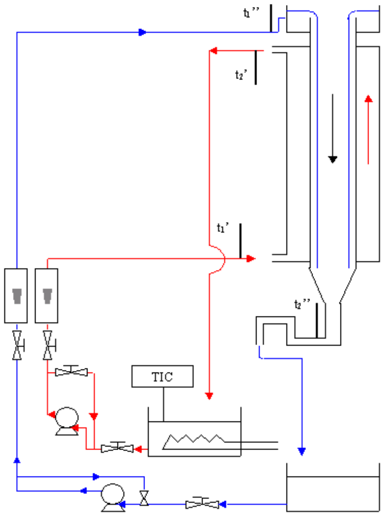

Figure 1. Diagram of the experimental device.

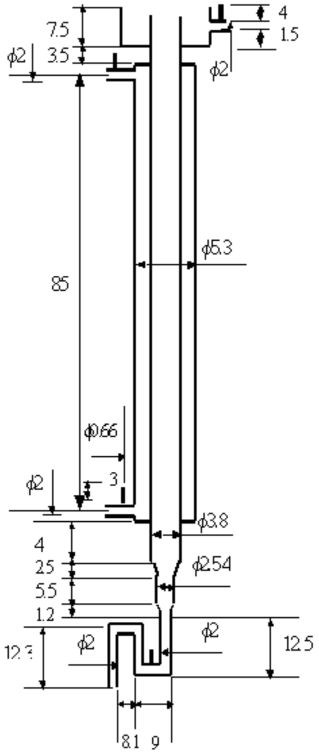

Figure 2. Diagram of the column (all dimensions are cm). All diameters are external. The width of the wall is 2 mm. Dimensions marked ϕ are external diameters.

evaporation of substances that can not be heated directly, and for high-viscosity and temperature-sensitive products. In this paper, the construction of a simple device is presented and elementary experiments with water from which the heat-transfer coefficient can be obtained are discussed. Additionally, experimental data can be compared with a correlation found in literature.

Experimental

Setup. The experimental setup is shown in Figure 1. It consists of a two-concentric-tube exchanger with the hot liquid flowing outside of the inner tube and the cold liquid flowing as a film inside the inner tube. The cold circuit is shown in blue and the hot circuit in red. A rotary meter and a valve are used to regulate the flow rate in each line. Temperatures at the entrance and exit of the tube are measured with thermocouples and represented by t_1'' and t_2'' in the cold line and t_1' and t_2' in the hot line.

Equipment. The required equipment is listed below.

A falling film exchanger (made of stainless steel).
A tank (50 L) for cold liquid
A tank (68 × 40 × 40 cm) with two electrical resistances, 1500 W each, 30 cm length, to heat the liquid
A pump for cold liquid (Flojet Model 2100-232)
A pump (specially suited for hot liquids) (5 to 30 L/min, 0.45 kW)
A stainless- steel rotary meter (250 to 2500 L/h) for the hot liquid
A stainless-steel rotary meter (40 to 450 L/h) for the cold liquid
5 thermocouples (k type)
A temperature indicator
A six-channel selector
A temperature indicator controller (TIC)
10 m of thermal insulate
12 m of plastic conductor (braided fiber glass)
5 needle valves and 4 ball valves
Switches, angle and T connections, clamps

The dimensions of the stainless-steel column are shown in Figure 2 and a photograph of the column is shown in Figure 3.

The wider element in the upper part of the column is the overflow system, which is responsible for the fluid falling as a film. This simple mechanism is shown in Figure 4 and the whole device is shown in Figure 5.

Results and Discussion

Theoretical Basis. In this system, the overall heat-transfer coefficient, *U*, can be determined from the following equation as a function of the individual heat-transfer coefficients (h', h''), the transfer areas (A', A'') on each side, the average logarithmic transfer area (A_{ml}), and the thermal conduction coefficient (k). Single primes represent the hot fluid and double primes represent the cold fluid.

$$\frac{1}{U''} = \frac{1}{h''} + \frac{e}{k\left(\dfrac{A_{ml}}{A''}\right)} + \frac{1}{h'\left(\dfrac{A'}{A''}\right)} \qquad (4)$$

where h'' is the sole unknown parameter. The values of e, A', A'', and A_{ml} are determined from the exchanger dimensions.

The overall coefficient U is deduced from

$$Q = UA''\Delta t_{ml} \qquad (5)$$

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Figure 3. Photograph of the entire device.

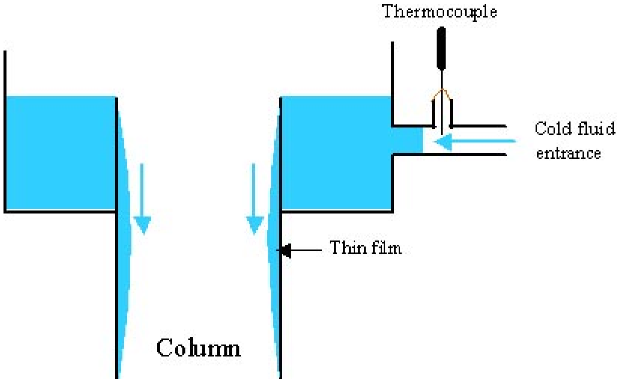

Figure 4. Overflow system.

Figure 5. Photograph of the whole installation.

where Q is the heat flow and Δt_{ml} is the average logarithmic temperature.

$$Q = m'c'(t_1' - t_2') = m''c''(t_2'' - t_1'') \tag{6}$$

where m' *and* m'' are the mass-flow rates and c' and c'' are the heat capacities for the hot and cold fluids, respectively.
Δt_{ml} for countercurrent systems takes the following value

$$\Delta t_{\mathrm{ml}} = \frac{(t_2' - t_1'') - (t_1' - t_2'')}{\left(\ln \dfrac{(t_2' - t_1'')}{(t_1' - t_2'')}\right)} \tag{7}$$

For liquids flowing countercurrently, the individual heat-transfer coefficient in the hot side, h', can be estimated from the Dittus–Boelter correlation if the turbulent regime ($Re >$ 10,000) is achieved.

$$\frac{h' D_{\mathrm{e},Nu}}{K} = 0.023\left[\frac{V D_{\mathrm{e},Re}\,\rho}{\mu}\right]^{0.8}\left[\frac{c\mu}{K}\right]^{0.4} \quad (\text{for } Re > 10{,}000) \tag{8}$$

In eq 8, $D_{\mathrm{e},Re}$ is the equivalent diameter used to calculate the Reynolds number ($4S/Z$, see eq 2), and $D_{\mathrm{e},Nu}$ is the equivalent diameter used to calculate the Nusselt number (about equal to $D_{\mathrm{e},Nu}$ in this case).

Physical properties of the fluid can be found in the literature [7, 8, 9]. If there are heat losses to the exterior, $D_{\mathrm{e},Re}$ can be considered equal to $D_{\mathrm{e},Nu}$.

When the transition regime is achieved ($2{,}100 < Re <$ 10,000), h' can be calculated from the Nusselt number, Nu, using a typical correlation for circular tubes:

$$Nu^{10} = Nu_{\mathrm{l}}^{10}\left[\frac{\exp\left[(2{,}200 - Re)/365\right]}{Nu_{\mathrm{l}}^{2}} + \frac{1}{Nu_{\mathrm{t}}^{2}}\right]^{-5} \tag{9}$$

The subscripts l and t represent laminar and turbulent conditions, respectively. Nu_{l} is equal to 3.657 for constant wall temperature or 4.364 for constant heat flow through the wall.

$$Nu_{\mathrm{t}} = Nu_0 + \frac{0.079(f/2)^{1/2} RePr}{(1 + Pr^{4/5})^{5/6}} \tag{10}$$

where Nu_0 (the Nusselt number for Raleigh–Reynolds, $Ra \times Re$ = 0) is 4.8 for constant wall temperature or 6.3 for constant heat flow through the wall and f is the friction factor.

Assuming constant heat flow through the wall, f can be calculated from:

$$f = \mathrm{A} + \frac{\mathrm{B}}{Re^{1/m}} \tag{11}$$

where A and B are constants.

If the Reynolds number is between 2100 and 4000, A = 0.0054, B = 2.3×10^{-8} and $m = -2/3$. If the Reynolds number

Table 2. Parameters, b_1 and b_2, for Eq 12 for the Different Flow Regimes [5].

Re_{film}	b_1	b_2
< 80	1	1/3
100–420	0.93	1/3
> 400	0.435	7/12
> 420	0.369	1/2

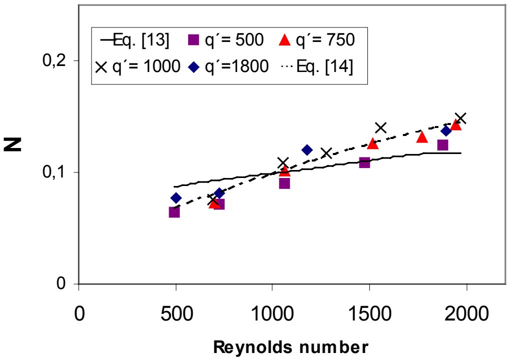

Figure 6. Comparison of results calculated from eq 13 and the best fit line calculated from eq 14.

is higher than 4000, A = 1.28 × 10^{-3}, B = 0.01143 and m = 3.2154.

To obtain the film thickness, e, we can use the following equation [5]

$$e = b_1 \left(\frac{3\mu''^2}{g} \right)^{1/3} Re_{film}^{b_2} \tag{12}$$

with

$$Re_{\text{film}} = \frac{v''}{D\pi\mu''} \tag{13}$$

where μ is the fluid viscosity, v is the kinematic viscosity, and g is the acceleration due to gravity. The parameters b_1 and b_2 can be obtained from literature [5] and are shown in Table 2 for different flow regimes. Laminar regime in the film is attained when Re_{film} is lower than 25, turbulent regime when Re_{film} is higher than 400. The transient regime is found in the intermediate case.

Operating Procedure

Cautions. Two cautions should be observed. First, ensure that the valves at the entrance and output of the pumps are open before switching on the pumps; second, keep an adequate level in the cold water depository to avoid overflow or an empty tank.

Operation. Switch on the hot-liquid pump when the water has reached 50 ºC, fixing the flow rate between 500 and 1800 L/h. Keep the flow rate constant during the experiments. Then, switch on the cold-water pump and fix a flow rate. All the temperatures and flows should be measured every 5 min. The stationary regime will be reached when two consecutive measurements are equal. This procedure should be repeated for 5 different flow rates of cold water. (It is recommended to begin with low flow rates and then increase them continuously).

Experimental Calculations

a.) Calculate Q using eq 6 for each cold-water flow rate
b.) Determine U using eq 5
c.) Calculate the Reynolds number in the hot fluid to obtain the flow regime.
d.) Calculate h' from eq 8 if the turbulent regime is achieved or from eqs 9 tthrough 11 if a transition regime is obtained.
e.) Use eq 4 to obtain h''.
f.) Calculate Re_{film} and the film thickness from eqs 12 and 13 using an average temperature.

The results are summarized in Tables 3 and 4. Additional information about the physical properties of water is given in Table 5.

The experimental results can be compared with those given by Bays and Mc Adams [10] for $Re_{\text{film}} < 2000$ (Reynolds results for the film are below 600):

$$\left(\frac{h}{\sqrt[3]{k^3 \rho^2 g / \mu^2}} \right)_{\text{film}} = 0.67 \left(\frac{4m}{Z\mu} \right)_{\text{film}}^{1/9} \left(\frac{c\mu^{5/3}}{kL\rho^{2/3} g^{1/3}} \right)_{\text{film}}^{1/3} \qquad [12]$$

$$(Re > 2000)$$

This equation can be written in terms of the nondimensional number, N, as:

$$N = 0.67\,\text{Re}^{1/9}\,\text{Pr}^{1/3} \tag{13}$$

Figure 6 shows the deviations between eq 13 and the experimental data. This is probably due to the temperature error range (± 0.5 ºC). If the temperature were obtained with better precision, results would probably improve.

An empirical correlation of the experimental data in the transient regime can be made by nonlinear fitting of the experimental data (Figure 6). The following equation is obtained

$$N = 0.00112\, Re^{0.581}\, Pr^{-0.060} \tag{14}$$

Conclusion

The students understanding of the thin-film phenomena explained in the classroom is augmented with a simple experiment using water in the laboratory. In addition, understanding of the effect of the Reynolds number on heat coefficients is improved. The experiment should be carried out by students in small (two student) groups. The use of spreadsheets to calculate coefficients, make drawings, and fit data is also useful.

Table 3. Experimental Results

q' (h^{-1})	q'' (h^{-1})	t_1' (ºC)	t_1'' (ºC)	t_2' (ºC)	t_2'' (ºC)	U'' (kcal hm^{-2})	h' $(\text{kcal hm}^{-2}\,{}^{\circ}\text{C}^{-1})$	h'' $(\text{kcal hm}^{-2}\,{}^{\circ}\text{C}^{-1})$	Re
500	40	48.5	16	47	37.5	455.5	1025.1	828.5	493.9
	60	50.5	15	49	36.5	494.6	1143.6	889.8	725.2
	100	48	14	46	28	514.3	982.5	1089.2	1062.5
	150	44.5	13	43	23	483.4	827.1	1147.7	1477.0
	200	42.5	12	41.5	20.5	472.4	736.2	1272.5	1881.4
750	60	49.5	14	48	36	601.9	2060.7	899.6	701.4
	100	47	13	45	29	696.8	2010.3	1143.8	1062.6
	150	43.5	12	42	26	761.9	1941.0	1358.9	1515.5
	180	42.5	12	41	24	771.1	1914.7	1400.7	1772.5
	200	41.5	12	40	23	795.5	1895.3	1494.0	1943.9
1000	60	50	14	48.5	35	643.6	2588.8	915.4	693.4
	100	47	13	45.5	31	775.1	2527.6	1218.9	1055.8
	120	45.5	13	44	29	813.9	2502.4	1323.9	1275.0
	150	43.5	13	42	27	889.4	2470.3	1546.8	1554.4
	200	40.5	13	39	23	893.7	2418.9	1578.9	1969.4
1800	40	50	16	49	39	740.5	3852.6	997.5	499.5
	60	50.5	16	49.5	37	758.5	3990.6	1022.0	725.2
	100	48	16	47	35	975.9	3787.3	1486.6	1182.2
	170	43	15	42.5	30.5	1018.0	3628.4	1612.9	1896.5
	200	40.5	15	39.5	26.5	1196.6	3563.8	2132.6	2111.9

Table 4. Calculation of the Film Thickness

q' (l/h)	q'' (l/h)	$T_m''^{*}$ (ºC)	$V \times 10^5$ $(m^3\,s^{-1})$	$\gamma_{\text{film}} \times 10^7$ $(m^2\,s^{-1})$	Re_{film}	δ (mm)
500	40	26.75	1.1	8.42	123.49	0.278
	60	25.75	1.7	8.61	181.31	0.321
	100	21	2.8	9.79	265.64	0.397
	150	18	4.2	10.6	369.26	0.466
	200	16.25	5.6	11.1	470.35	1.135
750	60	25	1.7	8.90	175.34	0.325
	100	21	2.8	9.79	265.64	0.397
	150	19	4.2	10.3	378.87	0.462
	180	18	5.0	10.6	443.12	0.496
	200	17.5	5.6	10.7	485.99	1.132
1000	60	24.5	1.7	9.00	173.35	0.326
	100	22	2.8	9.85	263.95	0.398
	120	21	3.3	9.79	318.76	0.422
	150	20	4.2	10.0	388.61	0.459
	200	18	5.6	10.6	492.35	1.131
1800	40	27.5	1.1	8.33	124.86	0.277
	60	26.5	1.7	8.61	181.31	0.321
	100	25.5	2.8	8.80	295.56	0.383
	170	22.75	4.7	9.32	474.14	0.466
	200	20.75	5.6	9.85	527.98	1.125

Table 5. Some Physical Properties of Water

T (ºC)	10	20	30	38	40	50	60	93
ρ $(g\,cm^{-3})$	0.99970	0.99821	0.99565		0.99222	0.98803	0.98320	
C $(J\,kg^{-1})$	4.1921	4.1818	4.1784		4.1785	4.1806	4.1843	
μ $(kg\,m^{-1}\,h^{-1})$	4.7052	3.6072	2.8717		2.35152	1.9692	1.6794	
k (kcal/hm^{2}ºC/m)	0.495			0.552				0.588

Nomenclature

A, B = constants

A = transfer area

c = isobaric heat capacity

d = column diameter not filled by the fluid film

D = column diameter

e = film thickness

f = friction factor

g = acceleration of gravity

G = mass flow velocity

h = individual heat transfer coefficient

k = thermal conduction coefficient

L = column length

m = mass flow

Nu = Nusselt number

Pr = Prandtl number

Q = heat

Re = Reynolds number

S = column section

t = temperature

U = overall heat transfer coefficient

ν = kinematic viscosity

Z = wet perimeter

μ = fluid viscosity

ρ = fluid density

Subscripts

e = equivalent

l = laminar

ml = average logarithmic

t = turbulent

$'$ = hot fluid (superscript)

$''$ = cold fluid (superscript)

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