# Designing a helical-coil heat exchanger

An HCHE offers advantages over a double-pipe heat exchanger in some situations. Here are a few cases where you might want to consider using one, and a simple procedure for designing it.

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☐ The double-pipe heat exchanger would normally be used for many continuous systems having small to medium heat duties. However, the helical-coil heat exchanger (HCHE) might be a better choice in some cases:

■ Where space is limited, so that not enough straight pipe can be laid.

■ Under conditions of laminar flow or low flowrates, where a shell-and-tube heat exchanger would become uneconomical because of the resulting low heat-transfer coefficients.

■ Where the pressure drop of one fluid is limited (for example, because of flow through other process equipment). By setting the velocity of the annulus fluid in an HCHE at about 1 m/s, the pressure drop will be low.

An HCHE consists of a helical coil fabricated out of a metal pipe that is fitted in the annular portion of two concentric cylinders, as shown in Fig. 1. The fluids flow inside the coil and the annulus, with heat transfer taking place across the coil wall. The dimensions of both cylinders are determined by the velocity of the fluid in the annulus needed to meet heat-transfer requirements.

Fig. 2 is a schematic cutaway view of the HCHE. The minimum clearances between the annulus walls and the coil and between two consecutive turns of the coil must be equal. In this case, both clearances are taken as $d_o/2$. The pitch, $p$, which is the spacing between consecutive coil turns (measured from center to center), is $1.5d_o$. Assuming that the average fluid velocity is uniform, the mass velocity of the fluid, $G_s$, is computed based on the minimum clearance between the helix and the cylinder wall.

## Design procedure

Here is a simple procedure for designing an HCHE:

*Determine the heat-transfer coefficients.* To calculate the heat-transfer coefficients in the coil and the annulus, the following parameters must be known:

1. The length of coil, $L$, needed to make $N$ turns:

$$L = N\sqrt{(2\pi r)^2 + p^2} \quad (1)$$

2. The volume occupied by the coil, $V_c$:

$$V_c = (\pi/4)d_o^2L \quad (2)$$

3. The volume of the annulus, $V_a$:

$$V_a = (\pi/4)(C^2 - B^2)pN \quad (3)$$

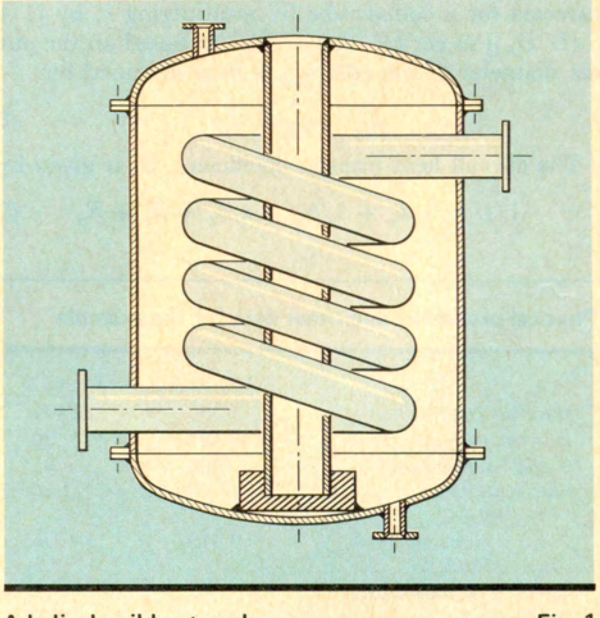
4. The volume available for the flow of fluid in the annulus, $V_f$:

$$V_f = V_a - V_c \quad (4)$$

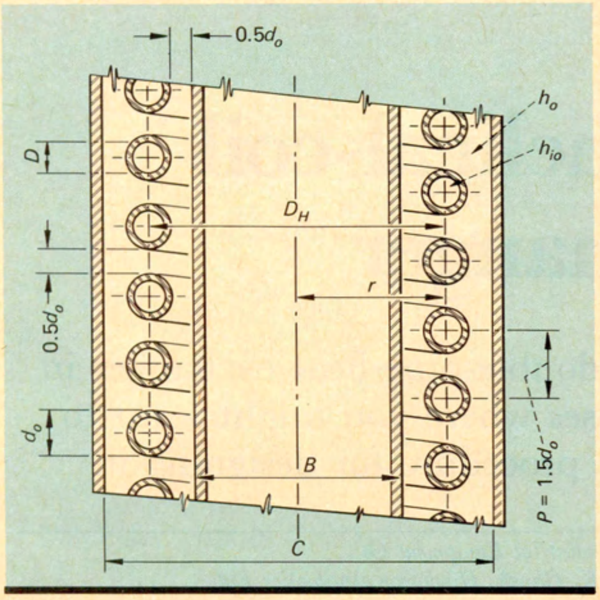
5. The shell-side equivalent diameter of the coiled tube, $D_e$:

$$D_e = 4V_f/\pi d_oL \quad (5)$$

The heat-transfer coefficient in the annulus, $h_o$, can



A helical-coil heat exchanger **Fig. 1**




Schematic cutaway view of an HCHE — Fig. 2

now be calculated using one of the following two equations. For Reynolds numbers, $N_{Re}$, in the range of 50–10,000, Eq. (6) [3] is recommended:

$$h_oD_e/k = 0.6N_{Re}^{0.5}N_{Pr}^{0.31} \quad (6)$$

For $N_{Re}$ over 10,000, Eq. (7) [4] should be used:

$$h_oD_e/k = 0.36N_{Re}^{0.55}N_{Pr}^{1/3}(\mu/\mu_w)^{0.14} \quad (7)$$

The heat-transfer coefficient of the fluid flowing inside the coil, $h_{io}$, can be determined using conventional methods, such as described in Ref. [4]. The heat-transfer coefficient based on the inside coil diameter, $h_i$, is obtained using a method for a straight tube—either one of the Sieder-Tate relationships, or a plot of the Colburn factor, $j_H$, vs. $N_{Re}$, such as Fig. 3. That must then be corrected for a coiled tube by multiplying $h_i$ by $[1 + 3.5(D/D_H)]$ to get $h_{ic}$. The coefficient based on the outside diameter of the coil, $h_{io}$, is then obtained by:

$$h_{io} = h_{ic}(D/d_o) \quad (8)$$

The overall heat-transfer coefficient, $U$, is given by:

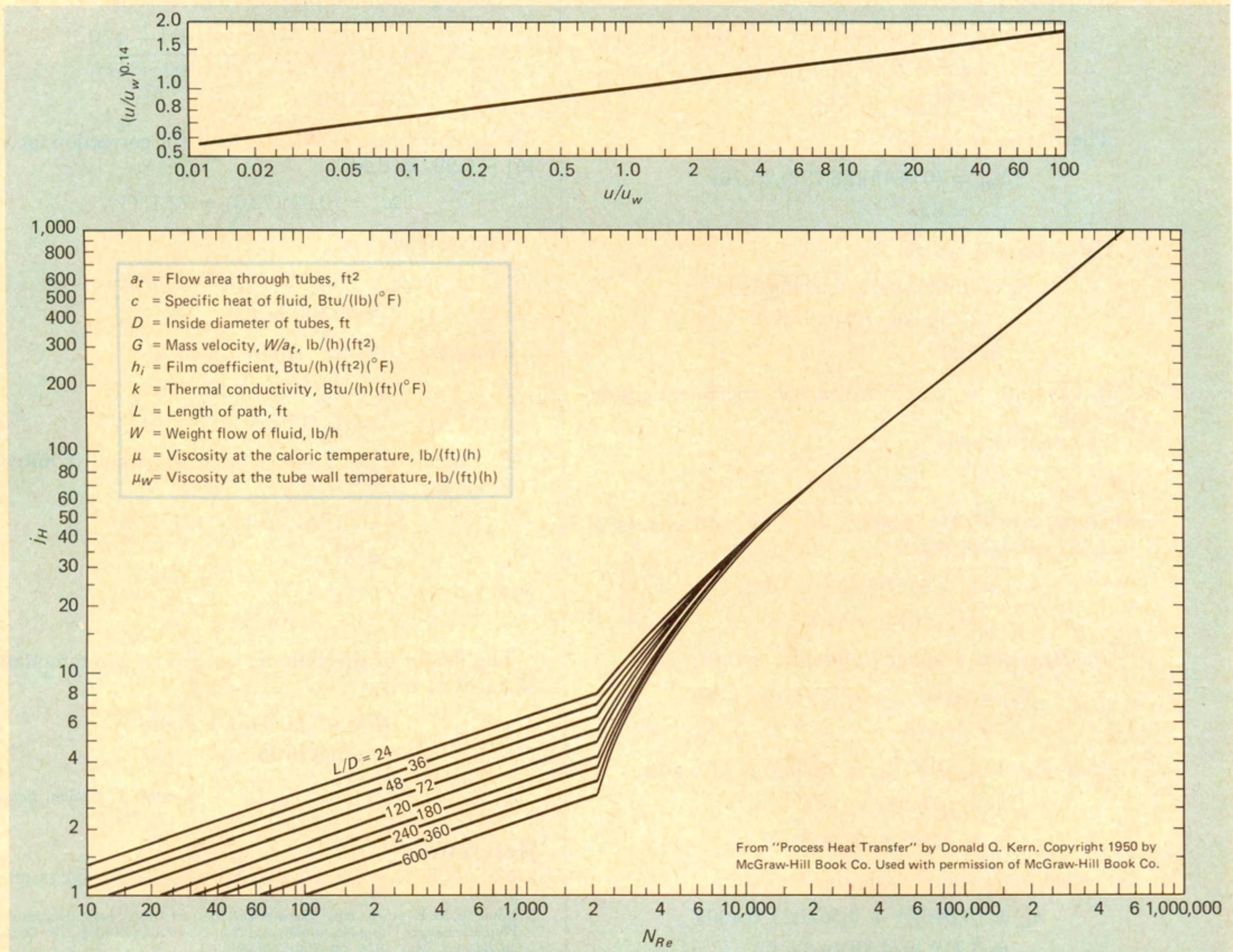
$$1/U = 1/h_o + 1/h_{io} + x/k_c + R_t + R_a \quad (9)$$

**Physical properties and other data for the example**

| | Liquid A | Liquid B |
|---|---|---|
| Mass flowrate, $M$, kg/h | 1,350 | 2,141 |
| Inlet temperature, °C | 127 | 30 |
| Outlet temperature, °C | 100 | 47 |
| Heat capacity, $c_p$, kcal/(kg)(°C) | 1.00 | 1.00 |
| Thermal conductivity, $k$, kcal/(h)(m)(°C) | 0.419 | 0.4075 |
| Viscosity, $\mu$, kg/(m)(h) | 1.89 | 5.76 |
| Density, $\rho$, kg/m³ | 870.0 | 935.0 |

## Nomenclature

- $A$ Area for heat transfer, m²
- $A_a$ Area for fluid flow in annulus, $(\pi/4)[(C^2 - B^2) - (D_{H2}^2 - D_{HI}^2)]$, m²
- $A_f$ Cross-sectional area of coil, $\pi D/4$, m²
- $B$ Outside dia. of inner cylinder, m
- $C$ Inside dia. of outer cylinder, m
- $c_p$ Fluid heat capacity, kcal/(kg)(°C)
- $D$ Inside dia. of coil, m
- $D_e$ Shell-side equivalent dia. of coil, m
- $D_H$ Average dia. of helix, m
- $D_{HI}$ Inside dia. of helix, m
- $D_{H2}$ Outside dia. of helix, m
- $d_o$ Outside dia. of coil, m
- $G_s$ Mass velocity of fluid, $M/[(\pi/4)((C^2 - B^2) - (D_{H2}^2 - D_{HI}^2))]$, kg/(m²)(h)
- $H$ Height of cylinder, m
- $h_i$ Heat-transfer coefficient inside straight tube, based on inside dia., kcal/(h)(m²)(°C)
- $h_{ic}$ Heat-transfer coefficient inside coiled tube ($h_i$ corrected for coil), based on inside dia., kcal/(h)(m²)(°C)
- $h_{io}$ Heat-transfer coefficient inside coil, based on outside dia. of coil, kcal/(h)(m²)(°C)
- $h_o$ Heat-transfer coefficient outside coil, kcal/(h)(m²)(°C)
- $j_H$ Colburn factor for heat transfer, $(h_iD/k)(N_{Pr})^{-1/3}(\mu/\mu_w)^{-0.14}$, dimensionless
- $k$ Thermal conductivity of fluid, kcal/(h)(m)(°C)
- $k_c$ Thermal conductivity of coil wall, kcal/(h)(m)(°C)
- $L$ Length of helical coil needed to form $N$ turns, m
- $M$ Mass flowrate of fluid, kg/h
- $N$ Theoretical number of turns of helical coil
- $n$ Actual number of turns of coil needed for given process heat duty ($N$ rounded to the next highest integer)
- $N_{Pr}$ Prandtl number, $c_p\mu/k$, dimensionless
- $N_{Re}$ Reynolds number, $Du\rho/\mu$ or $DG/\mu$, dimensionless
- $Q$ Heat load, kcal/h
- $q$ Volumetric flowrate of fluid, m³/h
- $r$ Average radius of helical coil, taken from the centerline of the helix to the centerline of the coil, m
- $R_a$ Shell-side fouling factor, (h)(m²)(°C)/kcal
- $R_t$ Tube-side fouling factor, (h)(m²)(°C)/kcal
- $\Delta t_c$ Corrected log-mean-temperature-difference, °C
- $\Delta t_{lm}$ Log-mean-temperature-difference, °C
- $u$ Fluid velocity, m/h
- $U$ Overall heat-transfer coefficient, kcal/(h)(m²)(°C)
- $V_a$ Volume of annulus, m³
- $V_c$ Volume occupied by $N$ turns of coil, m³
- $V_f$ Volume available for fluid flow in the annulus, m³
- $x$ Thickness of coil wall, m
- $\mu$ Fluid viscosity at mean bulk-fluid temperature, kg/(m)(h)
- $\mu_w$ Fluid viscosity at pipe-wall temperature, kg/(m)(h)
- $\rho$ Fluid density, kg/m³




**Colburn factor vs. Reynolds number for tube-side heat transfer** **Fig. 3**

*Determine the required area.* The area needed for heat transfer is determined by:

$$A = Q/U\Delta t_c \quad (10)$$

The log-mean-temperature-difference, $\Delta t_{lm}$, must be corrected to take into account the fact that the fluids are flowing perpendicular to each other, which is done by applying the standard correction factor for perpendicular flow [4].

*Determine the number of turns of coil.* Since $A = \pi d_o L$, and $L$ is expressed in terms of $N$, the number of turns of coil needed can be calculated by:

$$N = A/(\pi d_o(L/N)) \quad (11)$$

The actual number of coil turns needed, $n$, is simply $N$ rounded to the next highest integer.

## An example

Liquid A flows inside a 316 stainless-steel pipe coil; Liquid B, in the annulus. The flowrates, the inlet and outlet temperatures, and the physical properties of the fluids are given in the table. The geometry of the HCHE is that shown in Fig. 2, where $B = 0.340$ m; $C = 0.460$ m; $D = 0.025$ m; $D_H = 0.400$ m; $d_o = 0.03$ m; and $p = 0.045$ m.

A. Calculate the shell-side heat-transfer coefficient, $h_o$.

From Eq. (1), the length of coil needed is:

$$L = N\sqrt{(2\pi(0.2)^2 + (0.045)^2}$$
$$= 1.257N$$

Using Eq. (2-4), the volume available for fluid flow in the annulus, $V_f$, is:

$$V_f = [(\pi/4)(0.46^2 - 0.34^2)(0.045)N] - [(\pi/4)(0.03)^2(1.257N)]$$
$$= 2.504 \times 10^{-3}N$$

The shell-side equivalent diameter is:

$$D_e = (4)(2.504 \times 10^{-3}N)/(\pi)(0.03)(1.257N)$$
$$= 0.0845 \text{ m}$$

The mass velocity of the fluid is:

$$G_s = (2{,}141)/[(\pi/4)((0.46^2 - 0.34^2) - (0.43^2 - 0.37^2))]$$
$$= 56{,}792 \text{ kg/(m}^2\text{)(h)}$$

The Reynolds number is:

$$N_{Re} = (0.0845)(56{,}792)/(5.76)$$
$$= 833$$

Using Eq. (6), we get:

$$h_o = (0.6)(0.4075/0.0845)(833)^{0.5}((1)(5.76)/(0.4075))^{0.31}$$
$$= 190$$

B. Compute $h_{io}$, the heat-transfer coefficient inside the coil.

The fluid velocity is:

$$u = q/A_f$$

where $A_f = \pi D^2/4 = 4.909 \times 10^{-4}$ m$^2$ and $q = M/\rho = 1.552$ m$^3$/h, so that:

$$u = 1.552/(4.909 \times 10^{-4})$$
$$= 3{,}161.5 \text{ m/h}$$

The Reynolds number (tube-side) is then:

$$N_{Re} = (0.025)(3{,}161.5)(870)/(1.89)$$
$$= 36{,}383$$

From Fig. 3, $j_H$ (for $N_{Re} = 36{,}383$) is 110, and:

$$h_i = j_H(k/D)(N_{Pr})^{1/3}$$
$$= 3{,}046 \text{ kcal/(h)(m}^2\text{)(°C)}$$

Corrected for a coiled tube, this becomes:

$$h_{ic} = (3{,}046)[1 + 3.5(0.025/0.400)]$$
$$= 3{,}712 \text{ kcal/(h)(m}^2\text{)(°C)}$$

The heat-transfer coefficient based on the outside diameter of the coil is:

$$h_{io} = (3{,}712)(0.025/0.03)$$
$$= 3{,}093 \text{ kcal/(h)(m}^2\text{)(°C)}$$

C. Calculate the overall heat-transfer coefficient, $U$.

The coil-wall thickness, $x$, is:

$$x = (d_o - D)/2$$
$$= 0.0025 \text{ m}$$

The fouling factors, $R_t$ and $R_a$, depend on the nature of the liquids, the presence of suspended matter in the liquids, the operating temperatures, and the velocities of the fluids. In this case, both $R_a$ and $R_t$ are $8.2 \times 10^{-4}$ (h)(m$^2$)(°C)/kcal. The thermal conductivity of stainless steel is $k_c = 14$ kcal/(h)(m)(°C).

Using Eq. (9):

$$1/U = 1/190 + 1/3{,}093 + 0.0025/14 + 0.00082 + 0.00082$$
$$U = 135 \text{ kcal/(h)(m}^2\text{)(°C)}$$

D. Determine the required area.

The log-mean-temperature-difference is:

$$\Delta t_{lm} = \frac{[(127 - 30) - (100 - 47)]}{\ln((127 - 30)/(100 - 47))}$$
$$= 72.8\text{°C}$$

To account for perpendicular flow, the correction factor [6] is 0.99, so that:

$$\Delta t_c = (0.99)(72.8) = 72.1\text{°C}$$

The heat load is:

$$Q = (1{,}350)(1.0)(127 - 100)$$
$$= 36{,}450 \text{ kcal/h}$$

Using Eq. (10), the required area is:

$$A = (36{,}450)/(135)(72.1)$$
$$= 3.745 \text{ m}^2$$

E. Calculate the number of turns of coil required. From Eq. (11):

$$N = (3.745)/(\pi)(0.03)(1.257)$$
$$= 31.6$$

and:

$$n = 32$$

The height of the cylinder needed to accommodate 32 turns of coil is:

$$H = (32)(0.045) + (0.03)$$
$$= 1.470 \text{ m}$$

*Cynthia L. Fabian, Editor*

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