## Shell-and-tube Heat Exchanger Performance Lab

### Objectives

1. To observe and evaluate the performance of a shell-and-tube heat exchanger.

2. To compare the two methods of heat exchanger analysis: LMTD and Effectiveness-NTU.

3. To consider the validity of the assumptions required for heat exchanger analysis and to assess the error that may result from the assumptions.

### Introduction

Shell-and-tube heat exchangers are the most widely used type of heat exchanger. They can handle a variety of services in a wide range of allowable design pressures and temperatures, from full vacuum to 41 MPa (6000 psig) and from cryogenic temperatures to 1100°C (2000°F). Thus, this class of heat exchangers is the most versatile and finds application in the process, power, petrochemical, and refrigeration industries.

If several pipes are placed together within a shell, the classical single-tube-pass shell-and-tube arrangement results. A schematic of this type of arrangement is shown in Figure 1. Baffles are usually placed within the shell to promote higher heat transfer rates and to increase the overall effectiveness of the tubes. The baffles result in an increased heat transfer coefficient on the outside of the tubes by inducing turbulence and a cross-flow velocity component. A plenum is often provided for the tubes at one end such that a two-tube pass arrangement is created, as shown in Fig. 2. A variety of other types of arrangements are possible, such as multiple shell passes and even multiple (two, four, etc.) tube passes.

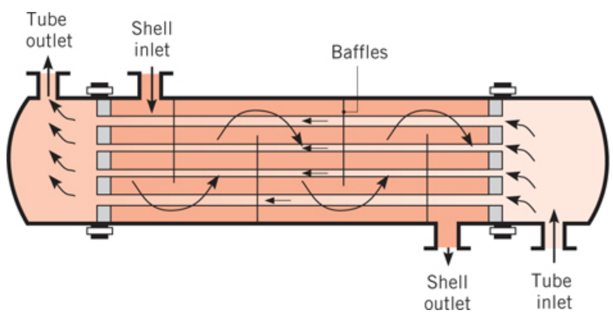


**Fig. 1** Single tube pass shell-and-tube heat exchanger, parallel operation.

Two methods of analysis are available for heat exchangers, the Log Mean Temperature Difference Method (LMTD Method) and the Effectiveness-Number of Transfer Units Method (Effectiveness-NTU Method). The LMTD Method was the first method developed for heat exchangers and is still widely used. The Effectiveness-NTU Method is the more recent method and is generally preferred for both analysis and design. Both methods will yield the same answer for a given problem, so uniqueness is satisfied.

For both methods, a number of simplifying assumptions are made, including: 1) the average overall heat transfer coefficient $U$ is constant throughout the exchanger, 2) the specific heat and mass flow rate, and hence the heat capacity rate, of each fluid are constant, 3) heat transfer between the heat exchanger and its surroundings is neglected, 4) axial conduction in both fluids and the tube walls is neglected, and 5) each fluid may be characterized by a single temperature (i.e., perfect transverse mixing in each fluid is presumed) at any cross section. Under these assumptions, the heat transfer between the hot and cold fluids is expressed as

$$q = C_c(T_{c,o} - T_{c,i}) \tag{1}$$

$$q = C_h(T_{h,i} - T_{h,o}) \tag{2}$$

where $$C_c = \dot{m}_c c_{pc} \tag{3}$$

$$C_h = \dot{m}_h c_{p,h} \tag{4}$$

the subscripts $h$ and $c$ refer to the hot and cold fluids, respectively, and the subscripts $i$ and $o$ refer to in and out, respectively. $C_h$ and $C_c$ are the hot and cold fluid heat capacity rates, $\dot{m}$ is the fluid mass flow rate and $c_p$ is the fluid specific heat at constant pressure. Since the temperature is changing continuously between the inlet and outlet, we will calculate fluid properties $c_{p,c}$ and $c_{p,h}$ based on the average temperature. For example, $c_{p,c}$ should be taken at $(T_{c,i}+T_{c,o})/2$.

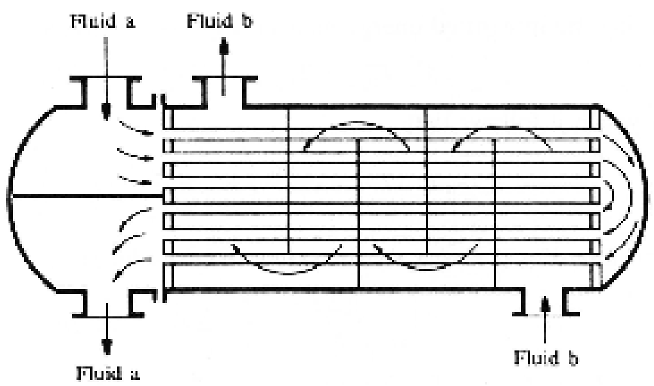


**Fig. 2** Two tube pass shell-and-tube heat exchanger. (From F.P. Incropera and D.P. DeWitt, *Fundamentals of Heat Transfer*, John Wiley and Sons, Inc., 1981.)

**LMTD Method**

The interfluid heat transfer may also be expressed as

$$q = U_i A_i F \Delta T_{lm} \tag{5}$$

where $U_i$ = the overall heat transfer coefficient based on the inside tube surface area
$A_i$ = the tube inside surface area
$F$ = correction factor
$\Delta T_{lm}$ = log mean temperature difference

Equation (5) may also be expressed in a form that replaces $U_iA_i$ *with* $U_oA_o$, where the overall heat transfer coefficient $U_o$ is based on the total outside surface area of the tubes $A_o$. The log mean temperature difference is the appropriate temperature difference to use in eq. (5), which is essentially just Newton's Law of Cooling for the heat exchanger. To determine the log mean temperature difference, the four fluid temperatures are assumed to be occurring in a counterflow heat exchanger, as shown in Fig. 3. Defining

$$\Delta T_1 = T_{h,i} - T_{c,o} \tag{6}$$

$$\Delta T_2 = T_{h,o} - T_{c,i} \tag{7}$$

allows the log mean temperature difference to be expressed as

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_1)} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)} \tag{8}$$

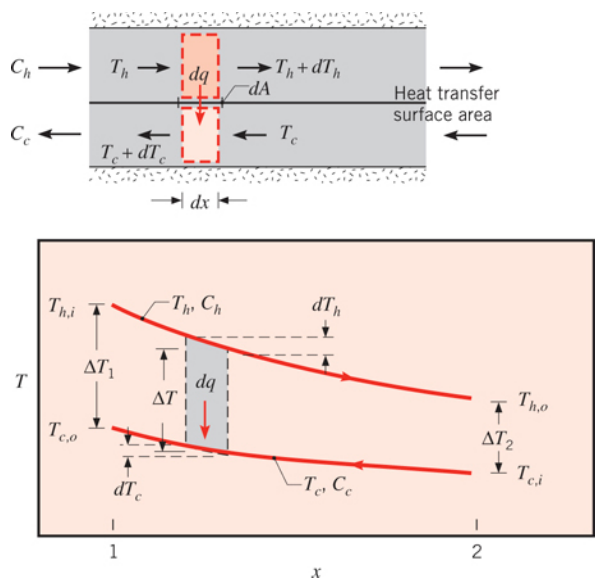


**Fig. 3** Temperature distributions for a counterflow heat exchanger.

The correction factor $F$ must be applied for heat exchangers not operating in counterflow. Note that the hot fluid (and, conversely, the cold fluid) may be either on the tube side or the shell side. Recall, for the counterflow single tube pass shell-and-tube heat exchanger, $F = 1$, and the log mean temperature difference is defined by eq. (8).

**Effectiveness-NTU Method**

The heat exchanger effectiveness ε is the ratio of the actual heat transfer rate to the maximum heat transfer rate, expressed as

$$q = \varepsilon C_{min} (T_{h,i} - T_{c,i}) \tag{9}$$

where $C_{min}$ is the smaller of $C_c$ and $C_h$, while $C_{max}$ is the larger of the two capacity values. For any heat exchanger it may be shown that

$$\varepsilon = \mathrm{f}(NTU, C_r) \tag{10}$$

where $C_r = C_{min} / C_{max}$ (11)

$$NTU = U_i A_i / C_{min} = U_o A_o / C_{min} \tag{12}$$

and NTU represents the Number of Transfer Units, a dimensionless parameter that is widely used in heat exchanger analysis. The actual functional form expressed by eq. (10) depends on the type of heat exchanger. The $\varepsilon$ and NTU relations for the counterflow single-tube-pass shell-and-tube heat exchanger are given below.

*Counterflow Single Tube Pass Shell-and-tube*

$$\varepsilon = \frac{1 - \exp\left[-NTU\left(1 - C_r\right)\right]}{1 - C_r \exp\left[-NTU\left(1 - C_r\right)\right]} \qquad (C_r < 1) \tag{13}$$

$$\varepsilon = \frac{NTU}{1 + NTU} \qquad (C_r = 1) \tag{14}$$

$$NTU = \frac{1}{C_r - 1} \ln\left[\frac{\varepsilon - 1}{\varepsilon C_r - 1}\right] \qquad (C_r < 1) \tag{15}$$

$$NTU = \frac{\varepsilon}{1 - \varepsilon} \qquad (C_r = 1) \tag{16}$$

## Experimental Apparatus

The fixed tube bundle heat exchanger from the Young Radiator Company for this experiment has the characteristics listed in Table 1.

Table 1. Shell-and-tube heat exchanger (Young Radiator Company) specifications

| Feature | Model HF-201-HY-1P |
|---|---|
| Shell Outside Diameter (in) | 2.12 |
| Shell (and Tube) Length (in) | 9.00 |
| Baffle Spacing (in) | 1.13 |
| Tube Outside Diameter (in) | 0.250 |
| Tube Wall Thickness (in) | 0.028 |
| Number of Tubes | 31 |
| Number of Tube Passes | 1 |
| Tube Material | copper |
| Shell Material | brass |

The heat exchanger is instrumented with type-T thermocouples, providing temperatures for both fluids at the inlets and outlets, and the shell and ambient temperatures. The thermocouples are connected to a digital thermometer, which converts the thermocouple analog signal to a digital reading. Water is supplied to both the tube side and shell side of the heat exchanger. In-line rotameters, providing a measure of volumetric flow rate in gallons per minute (gpm), are connected in both the hot and cold water lines. Hot water is provided via a recirculating loop consisting of a hot water tank with electrical resistive heaters with a temperature controller, a rotameter, a pump, the heat exchanger, and various valves. Cold water is provided via connection to the building domestic water supply and drains into the building water drain system. A schematic of the test apparatus is shown in Fig. 4.

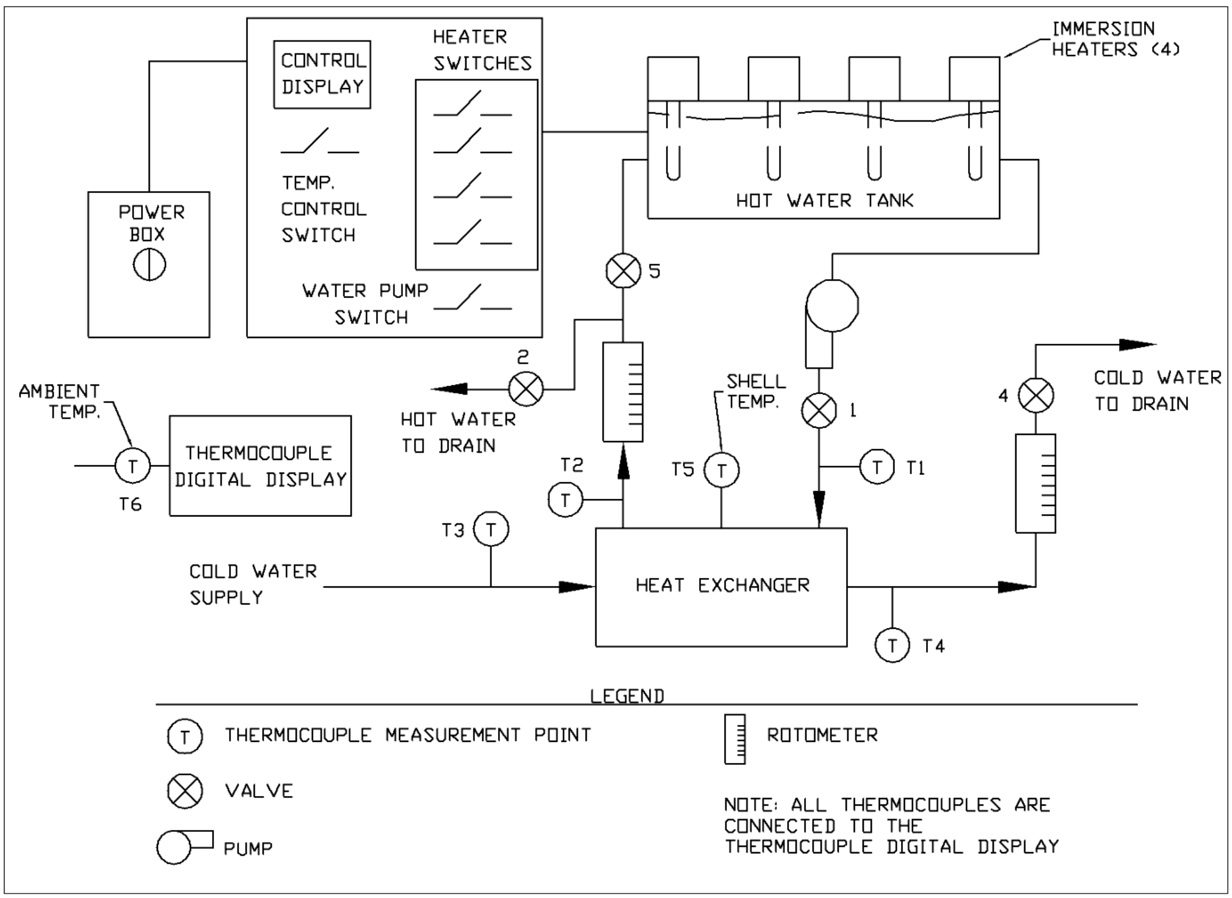


**Fig. 4.** Schematic of the test apparatus

## Procedure

1. Determine the flow direction of each fluid and the fluid type (hot or cold) on the tube-side and shell-side.

2. Examine the water level in the vertical pipe connected to the hot-water tank. If instructed by your TA, add water to the tank until water free surface is visible a few inches below the top of

the pipe. Use valve V-2 and the faucet for the hot-water supply line emerging from the floor below the back of the sink.

3. Your TA will direct you to open the faucet for the cold-water supply line emerging from the floor below the back of the sink. Then set the cold-water control valve on the outlet side of the heat exchanger (valve V-4 downstream of the rotameter) to about 5-6 gpm. Always use the cold-water control valve to set and control the flow rate. Always maintain the cold-water flow rate at greater than 3 gpm. It is recommended that the combined flow rates for the hot and cold fluids be less than 10 gpm.
4. When instructed by your TA:
    a. Open the hot-water control valve on the inlet side of the heat exchanger (valve V-1).
    b. Open the hot-water control valve on the outlet side of the heat exchanger (near the hot-water tank inlet, valve V-5).
    c. Turn on power to all equipment using the large red switch on the control panel.
    d. Turn on the power to the pump using the marked toggle switch.

5. Use the hot-water control valve (valve V-5) downstream of the rotameter to control the flow rate. Begin with this valve fully open, producing the maximum possible flow rate.

6. As directed by your TA, turn on the Temperature Controller. Set the desired temperature (indicated by SV – Set Value) as follows: Press the SV button. Press the up arrow key ($\wedge$) under the digit to be changed (digit should then be in a flashing mode). Use the up arrow ($\wedge$) and down arrow ($\vee$) keys to change the digit to the desired value. Press the Enter key (digit will stop flashing). Repeat this sequence for each digit to be changed. The hot water temperature should be set in the range from 90 to 130°F (32 – 54°C).

7. Turn on all 4 heaters using the individual toggle switches.

8. Monitor the outlet temperature from the hot-water tank using the Present Value (PV) display. Wait until steady state is reached (PV = SV on the display).

9. Use the digital thermometer with accompanying thermocouples to measure all system temperatures. Record all fluid temperatures, shell temperature, ambient temperature, and flow rates for the heat exchanger.

10. Reduce the hot fluid flow rate slightly (using valve V-5) and wait for a steady state condition. Record all temperatures and flow rates.

11. Keep the cold flow rate constant ($\dot{m}_c$) and reduce the hot flow rate ($\dot{m}_h$) by closing the hot-water control valve to at least its half-open position or less. Wait for a steady-state condition. Record all temperatures and flow rates.

12. Reduce the cold flow rate ($\dot{m}_c$) by approximately half by partially closing the cold-water valve V-4. Set the hot-water flow rate ($\dot{m}_h$) back to its maximum value by fully opening the hot-water valve. Wait for a steady-state condition. Record all temperatures and flow rates.

13. Keep the cold flow rate constant ($\dot{m}_c$) at the same flow rate used above, and reduce the hot

flow rate ($\dot{m}_h$) by closing the hot-water control valve to at least its half-open position or less. Wait for a steady-state condition. Record all temperatures and flow rates.

14. When instructed by your TA, shut down the heat exchanger apparatus using the following steps:
    a. Turn off all 4 heaters using the toggle switches.
    b. Turn off the Temperature Controller toggle switch.
    c. Allow the heaters to cool 3-5 minutes with the cold and hot water flowing. Then turn off the pump using the toggle switch.
    d. Shut off the cold water supply at valve V-4. Leave the control valves in their present positions.
    e. Turn off the digital thermometer if you are in the last lab of the day.

**Data Reduction**

For each data set, conduct the following data reduction process:

1. Compute the heat transfer rate $q$ using the tube-side (cold-side) data and eq. (1) to determine $C_c$, $C_h$, $C_{min}$, $C_{max}$, and $C_r$.

2. Compute $\Delta T_{lm}$ and $A_i$ (or $A_o$). Using these values and $q$ from step 1, compute $U_i$ (or $U_o$) from eq. (5).

3. Compute NTU from eq. (12).

4. Use NTU and $C_r$ to compute $\varepsilon$ from eq. (13) (or eq. (14) if $C_r = 1$).

5. Compute $\varepsilon$ using eq. (9) and compare to that determined in step 4.

6. Compare the <u>measured</u> shell-side outlet temperature $T_{s,o}$ to that <u>predicted</u> by theory. Given the inlet cold and hot temperatures ($T_{c,i}$ and $T_{h,i}$) along with the mass flow rates of both sides ($\dot{m}_c$ and $\dot{m}_h$), we can calculate the shell-side outlet temperature as follows. Since the shell-side is the hot-side in this case, we have $T_{s,o}=T_{h,o}$. Based on an energy balance of the hot-side, we have from eq. (2)

$$q = C_h \left(T_{h,i} - T_{h,o}\right)$$

Furthermore, based on the e-NTU method, we have from eq. (9)

$$q = \epsilon \, C_{min} \left(T_{h,i} - T_{c,i}\right)$$

Equating these two equations and solving for the hot-side outlet temperature gives

$$T_{h,o} = T_{h,i}\left(1 - \frac{\epsilon \, C_{min}}{C_h}\right) + T_{c,i}\left(\frac{\epsilon \, C_{min}}{C_h}\right) \qquad (17)$$

7. Estimate the heat transfer between the shell and the surroundings due to natural convection, $q_{conv}$. Approximate the shell as a circular cylinder.

8. Estimate the heat transfer between the shell and the surroundings due to radiation, $q_{rad}$. In order to do this, we will need to estimate the emissivity of the shell material (listed as brass by the manufacturer). If you consult engineeringtoolbox.com, for example, you will see that the emissivity for brass can vary from 0.03-0.6 depending on the surface finish and the oxidation. However, since the shell is painted gray, this raises the emissivity to approximately 0.95.

## Required Plots & Tables

1. Create a table that looks like the one below containing the values from your analysis. Note, cases 1a & 1b should have the same $\dot{m}_c$; and, cases 2a & 2b should have the same $\dot{m}_c$ (approximately half of that for cases 1a and 1b). In the table, Δε represents the percent difference between the values of ε calculated from the two different methods: eq. (13,14) and eq. (9). Also, $\Delta T$ represents the percent difference between the measured and predicted shell-outlet temperature.

| Case | Flow Rate | | $C_r$ | $U_i$ | ε | | | $T_{s,o}$ (°C) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\dot{m}_c$ (gpm) | $\dot{m}_h$ (gpm) | | (W/K m$^2$) | eq. 13 or 14 | eq. 9 | Δε (%) | measured | eq. 17 | $\Delta T$ (%) |
| 1a | | | | | | | | | | |
| 1b | | | | | | | | | | |
| 2a | | | | | | | | | | |
| 2b | | | | | | | | | | |

2. Create a table that looks like the one below containing the values from your analysis. In the table, $\Delta = q_{conv} + q_{rad}$.

| Case | Flow Rate | | heat transfer rate (W) | | | heat transfer modes (W) | | |
|---|---|---|---|---|---|---|---|---|
| | $\dot{m}_c$ (gpm) | $\dot{m}_h$ (gpm) | $q_c$ (eq. 1) | $q_h$ (eq. 2) | % diff | $q_{conv}$ | $q_{rad}$ | $\Delta/q_c$ (%) |
| 1a | | | | | | | | |
| 1b | | | | | | | | |
| 2a | | | | | | | | |
| 2b | | | | | | | | |

3. Download the Matlab figure file provided that shows ε versus NTU over a range of $C_r$ values for a counterflow heat exchanger. Note, this is the same figure as that displayed in Figure 5 below and Fig. 11.11 in Bergman et al. (2007). Plot your calculations of ε from eq. (9) on this figure using circle markers for cases 1a & 1b and square markers for cases 2a & 2b. Include a legend.

## Short-Answer Questions

1. Discuss the reasons for any discrepancies observed between the measured an calculated shell-outlet temperatures $T_{s,o}$ listed in Table 1.

2. Discuss any experimental conditions that you think could cause the disparities in the effectiveness ε values listed in Table 2. According to Bergman et al. (2007), values determined by the two methods should be the same.

3. How well do your effectiveness ε values plotted from item 3 above agree with the theoretical performance curves? Your response should include a percent difference for each test case and describe any trends observed, i.e., are there more errors with lower/higher NTU or lower/higher $C_r$?

## References


1. Bergman, T.L., Lavine, A.S., Incropera, F.P. and Dewitt, D.P., Fundamentals of Heat and Mass Transfer, 7th Ed., John Wiley & Sons, New York, 2011.

2. Gupta, J.P., *Working with Heat Exchangers*, Hemisphere Publishing, New York, 1990.

3. Hodge, B.K., *Analysis and Design of Energy Systems*, 2nd Ed., Prentice-Hall, Englewood Cliffs, New Jersey, 1990.


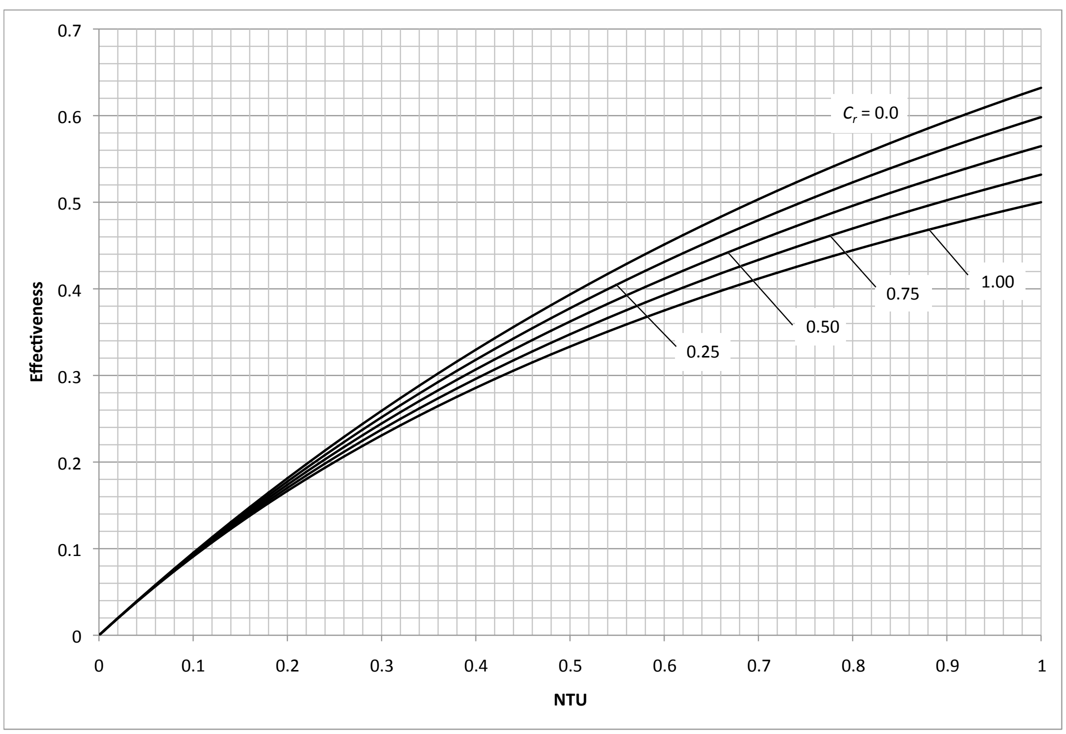


**Fig. 5** Effectiveness of a counterflow heat exchanger