PROC 5071:
Process Equipment Design I

Workbooks: Shell and tube heat exchanger design

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1 Workbook: Calculation of LMTD

1.1 The problem

A heat exchanger is to be used to subcool condensate from a methanol condenser from 95^oC to 40^oC. Flow rate of methanol $100,000kg/h$. Brackish water will be used as the coolant, with a temperature rise from 25^oC to 40^oC.

Considering a 1-2 shell and tube heat exchanger, calculate the corrected log mean temperature difference (LMTD).

1.2 Notes and analysis

- We will use the notations T and t for the hot and cold fluid temperature, respectively.
- For the ends, 1 is used for the inlet of the hot stream.
- For countercurrent, end 2 is the inlet for the cold fluid.

- Brackish water being corrosive, it's allocated to the tube side (why?).

1.3 Calculation steps

Step 1 : Calculate LMTD (Δ_{lm}) assuming a single pass countercurrent flow.

Step 1.1 : Identify the temperatures.

Using the above mentioned notations, for the countercurrent flow

$$\begin{aligned} T_1 &= \quad {}^oC \\ T_2 &= \quad {}^oC \\ t_1 &= 40^oC \\ t_2 &= \quad {}^oC \end{aligned}$$

Step 1.2 : Calculate ΔT_1 and ΔT_2.

$$\begin{aligned}\Delta T_1 &= T_1 - t_1\\ &= \\ &= \end{aligned}$$

$$\begin{aligned}\Delta T_2 &= T_2 - t_2\\ &= \\ &= \quad {}^oC\end{aligned}$$

Step 1.3 : Calculate ΔT_{lm}.

$$\begin{aligned}\Delta T_{lm} &= \frac{\qquad\qquad\qquad {}^oC}{\ln}\\ &= 30.8^oC\end{aligned}$$

Step 2 : Calculate the correction factor, F_T.

Step 2.1 : Calculate the constants R and S

- R is defined as the ratio of temperature decrease of the hot fluid to the temperature increase of the cold fluid

$$
\begin{aligned}
R &= \frac{T_1 - T_2}{t_1 - t_2} \\
&= \frac{(\quad - \quad)^oC}{(\quad - \quad)^oC} \\
&=
\end{aligned}
$$

- S is defined as the ratio of the temperature increase of the cold fluid to the difference between the inlet temperatures of the two fluids

$$
\begin{aligned}
S &= \frac{t_1 - t_2}{T_1 - t_2} \\
&= \frac{(\quad - \quad)^oC}{(\quad - \quad)^oC} \\
&=
\end{aligned}
$$

Step 2.2 : From the graph find the value of the correction factor.

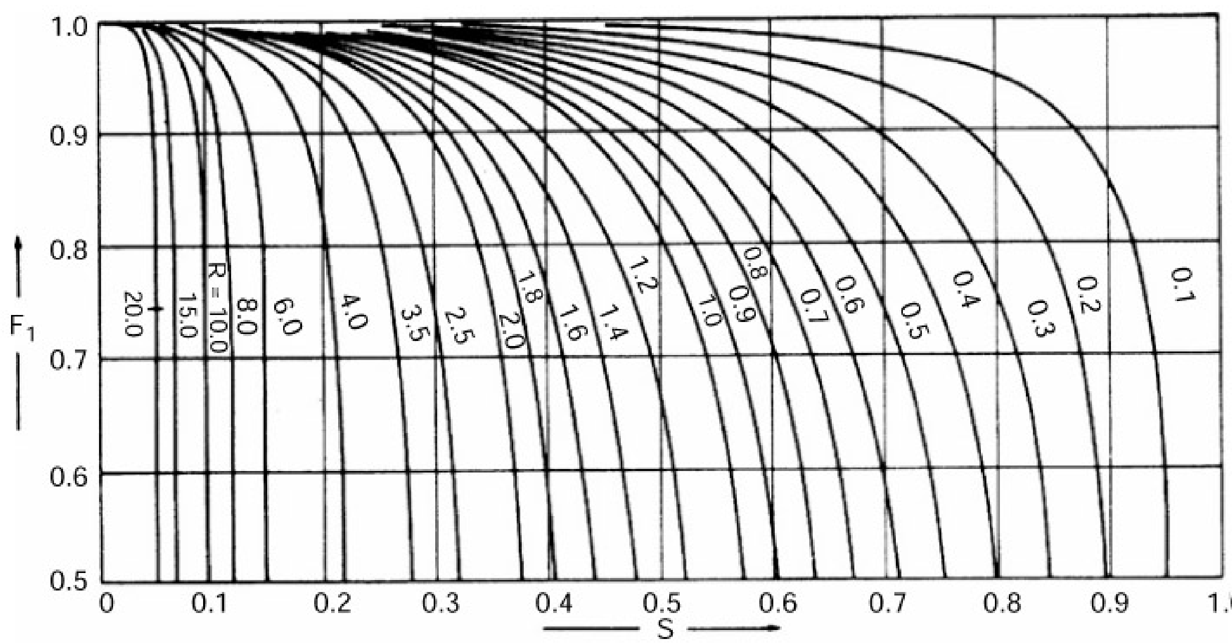

Figure 1: Temperature correction factor for 1-2 shell and tube heat exchangers.

Alternatively, the following equation can be used to calculate F_T.

$$F_T = \frac{\sqrt{R^2+1}\,\ln\left[\frac{1-S}{1-RS}\right]}{(R-1)\ln\left[\frac{2-S\left(R+1-\sqrt{R^2+1}\right)}{2-S\left(R+1+\sqrt{R^2+1}\right)}\right]}$$

The value of F_T is obtained as

$$F_T =$$

Step 3 : Calculate the corrected mean temperature.

$$\begin{aligned}\Delta T_m &= F_T \times \Delta T_{lm} \\ &= \quad \times 38^oC \\ &= \quad ^oC\end{aligned}$$

2 Workbook: Calculation of the tube side heat transfer coefficients

2.1 The problem

A heat exchanger is to be used to subcool condensate from a methanol condenser from 95^oC to 40^oC. Flow rate of methanol $100,000kg/h$. Brackish water will be used as the coolant, with a temperature rise from 25^oC to 40^oC.

Considering a 1-2 shell and tube heat exchanger, calculate the tube side heat transfer coefficient.

2.2 Additional information

- Brackish water in the tube side.
- Pipes to be used for the tube side has the specification: $3/4in$, $16ft$ that has the following dimensions
  $i.d. = 16mm, o.d. = 20mm, length = 4.88m$
- Table of fluid properties at average conditions

Table 1: Water properties.

Property	Value
ρ	$995 kg/m^3$
μ	$0.8 mN.s/m^2$
C_p	$4.2 kJ/kg.^oC$
k	$0.59 W/m.^oC$

Table 2: Methanol properties.

Property	Value
C_p	$2.84 kJ/kg.^oC$

2.3 Problem analysis

First look at the equation for determining the tube side heat transfer coefficient:

$$Nu = j_h Re Pr^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

with

$$Nu = \frac{h_t d_i}{k_f}$$

$$Re = \frac{d_i u_t \rho}{\mu}$$

$$Pr = \frac{c_p \mu}{k_f}$$

To determine h_t we need to know the following variables

- d_i: inner diameter of tubes - given
- k_f: conductivity of water - table
- ρ: density of water - table
- μ: viscosity of water - table
- C_p: specific heat of water - table
- μ_w: viscosity of water at wall temperature - table if t_w is known
- u_t: velocity of water in the tube - can be calculated

How to calculate u_t:

- We need to know flow rate of water, which can be calculated from heat duty
- We need to know the flow area of water.

- Flow area can be calculated if the tube $i.d$ (given) and number of tubes are known.
- To know number of tubes, we need heat transfer area.
- to know heat transfer area, we need to know the overall heat transfer coefficient (U).
- To calculate U we need h_t

This makes the calculation procedure an iterative problem. Fortunately we know how to solve problems iteratively!

So let's do it

2.4 Solution

1. First let us assume a value of the overall heat transfer coefficient based on the outside tube area.

$$U_o = 0.6\ kW/m^2.^oC$$

2. Calculate the heat duty. This can be done for

the hot fluid.

$$\begin{aligned} Q &= \left(\dot{m}C_p\Delta T\right)_{methanol} \\ &= (\qquad kg/h)(\qquad kJ/kg.^oC)(\qquad)^oC \\ &= \qquad kW \end{aligned}$$

3. Calculate the heat transfer area (outer surface area of tubes) from

$$Q = U_o A_o \Delta T_m$$

ΔT_m is the corrected LMTD. So we have

$$\begin{aligned} A_o &= \frac{Q}{U_o \Delta T_m} \\ &= \frac{\qquad}{\qquad} \\ &= \qquad m^2 \end{aligned}$$

4. Calculate the number of tubes
   - $o.d.$ of tubes $= 20mm$
   - Effective length $= 4.83m$

- Outside surface area of one tube

$$= \pi d_o L$$
$$=$$
$$= \qquad m^2$$

- Number of tubes

$$= \frac{\qquad}{\qquad}$$
$$=$$

5. Calculate the tube side flow area
   - Inside flow area for one tube

$$=$$
$$= \qquad mm^2$$

   - Total tubes = 916. As there are 2 passes, number of tubes per pass = (916/2) = 458.
   - Total flow area inside tube per pass

$$=$$
$$= \qquad m^2$$

6. Calculate fluid velocity inside tube
   - Mass flow rate of water can be obtained from heat duty

$$Q = \left(\dot{m} C_p \Delta T\right)_{water}$$

Giving

$$\dot{m}_{water} = \frac{Q}{\left(C_p \Delta T\right)_{water}}$$

$$= \frac{}{}$$

$$= \quad kg/s$$

   - Mass flux can be obtained using the flow area

$$G_{water} = \frac{\dot{m}_{water}}{0.092 m^2}$$

$$= \frac{}{}$$

$$= \quad kg/s.m^2$$

- Velocity is obtained using fluid density

$$u_t = \frac{G_{water}}{\rho}$$

$$= \overline{}$$

$$= \quad m/s$$

7. Now calculate Re and Pr

$$Re = \overline{}$$

$$= \overline{}$$

$$=$$

$$Pr = \frac{C_p\mu}{k_f}$$

$$= \overline{}$$

$$=$$

8. Obtain j_h using the value of Re from the attached graph. Note that you do not need $L.D$

for this value of Re.

$$j_h =$$

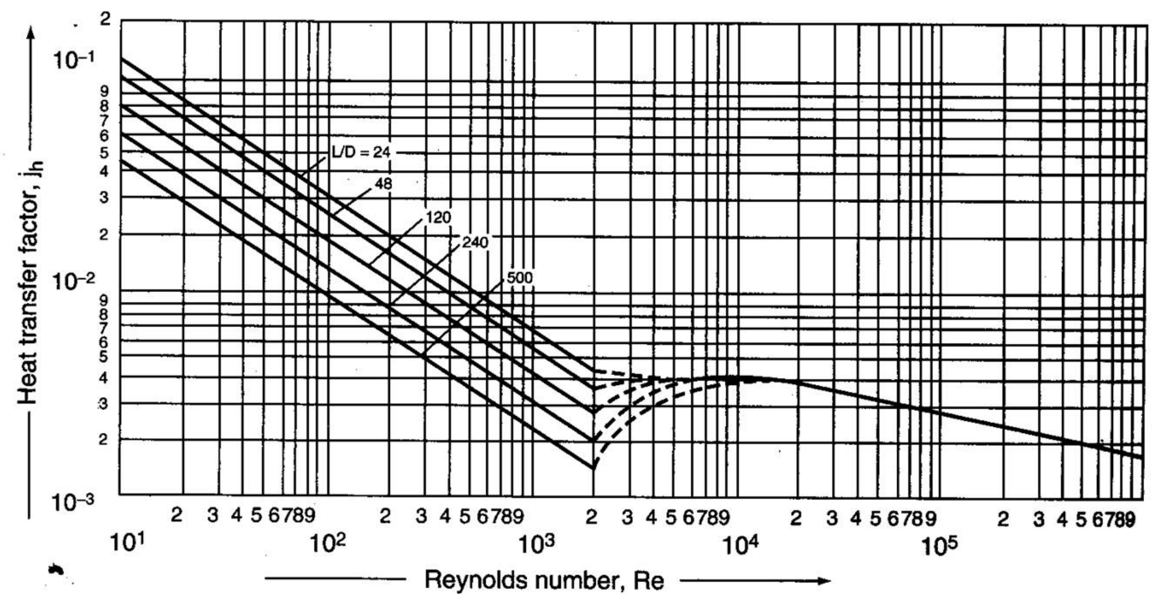

Figure 2: Tube side j_h factor.

9. Finally calculate Nu and obtain h_t by neglecting the viscosity correction term

$$\frac{h_t d_i}{k_f} =$$

$$=$$

$$=$$

So we get

$$
\begin{aligned}
h_t &= \underline{\hspace{3cm}} \\
&= \underline{\hspace{6cm}} \\
&= \qquad W/m^2.^oC
\end{aligned}
$$

Are we done? NOT YET!

- We started the calculation based on an assumed value of U. So we need to check whether that was right.
- To check that we need to estimate the shell side coefficient which will be our task for next workbook.
- Also we neglected the viscosity correction factor. To get that we need the wall temperature which also a part of the next workbook.

3 Workbook: Calculation of the shell side heat transfer coefficient

3.1 Problem statement

A heat exchanger is to be used to subcool condensate from a methanol condenser from 95^oC to 40^oC. Flow rate of methanol $100,000kg/h$. Brackish water will be used as the coolant, with a temperature rise from 25^oC to 40^oC.

Considering a 1-2 shell and tube heat exchanger, calculate the shell side heat transfer coefficient.

3.2 Additional information

- All information from the previous workbooks are valid.

Table 3: Methanol properties.

Property	Value
ρ	$750 kg/m^3$
μ	$0.34 mN.s/m^2$
C_p	$2.84 kJ/kg.^oC$
k	$0.19 W/m.^oC$

3.3 Analysis

First look at the equation for determining the shell side heat transfer coefficient:

$$Nu = j_h Re Pr^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

with

$$\begin{aligned} Nu &= \frac{h_s d_e}{k_f} \\ Re &= \frac{d_e u_s \rho}{\mu} \\ Pr &= \frac{c_p \mu}{k_f} \end{aligned}$$

To determine h_s we need to know the following variables

- d_e: equivalent diameter - calculate from tube dimensions and pitch
- k_f: conductivity of methanol - table
- ρ: density of methanol - table
- μ: viscosity of methanol - table
- C_p: specific heat of methanol - table
- μ_w: viscosity of methanol at wall temperature - table if t_w is known
- u_s: velocity of methanol in the shell - can be calculated

How to calculate u_s:

- We need to know flow rate of methanol, which is given
- We need to know the flow area of water.

- Flow area can be calculated if tube dimensions, pitch, shell dimensions and baffle configuration are known. To know all of these, we need heat transfer area.
- to know heat transfer area, we need to know the overall heat transfer coefficient (U).
- To calculate U we need h_s

Again this becomes an iterative problem
SO LET'S DO IT

3.4 Solution

1. From the tube side calculation, we get the number of tubes = 916.
2. Also the tube dimensions are given which are $i.d. = 16mm$ and $0.d. = 20mm$.
3. These tubes are to be placed in the shell and we need to know the size of the shell that can accommodate all these tubes. The diameter of

the tube bundle can be obtained from

$$D_b = d_o \left(\frac{N_t}{K_1} \right)^{\frac{1}{n_1}}$$

where, N_t is the number of tubs and n_1 and K_1 are constants that are given in the literature. For 2 tube passes the values are

$$K_1 = 0.249 \quad n_1 = 2.207$$

So we have

$$D_b = (\qquad) \left(\frac{}{} \right)^{\frac{1}{2.207}} = \qquad mm$$

For this problem we will use a split ring floating type head for which bundle diameter clearance is $68mm$. So we get the shell diameter as

$$D_s = \qquad mm + 68mm = \qquad mm$$

4. Calculate the velocoty/mass velocity of methanol in the shell side. For this we need to calculate the flow area which is the area between two baffles.

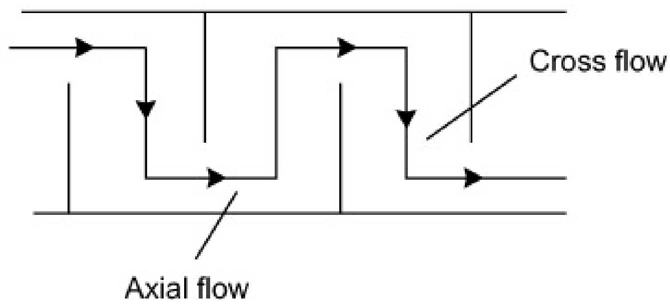

Figure 3: Simplified flow pattern of liquid in the shell.

- Choose baffle spacing as $\frac{1}{5}th$ of the shell diameter

$$Baffle\ spacing = \frac{D_s}{5} = \frac{\quad mm}{5} = 178mm$$

- Choose tube pitch as $1.25d_o$.

$$p_t = 1.25d_o = 1.25(\quad mm) = 25mm$$

- Cross flow area is obtained as

$$A_s = \left(\frac{}{}\right)(\quad)(\quad)mm^2 = \qquad m^2$$

- Mass velocity is obtained as

$$G_s = \frac{\dot{m}}{A_s} = \frac{100000kg/h}{\quad m^2}$$
$$= \quad kg/s.m^2$$

- The equivalent diameter is given by

$$d_e = \frac{1.1}{d_o}\left(p_t^2 - 0.907 d_o^2\right)$$

$$=$$

$$= \quad mm$$

5. Now calculate Re and Pr

$$Re = \rule{2cm}{0.4pt} = \rule{2cm}{0.4pt}$$

$$= \rule{10cm}{0.4pt}$$

$$=$$

$$Pr = \frac{C_p \mu}{k_f}$$

$$= \rule{14cm}{0.4pt}$$

$$=$$

6. Obtain j_h using the value of Re from the attached graph. Note that we will use a $25\%4$

baffle cut.

$$j_h =$$

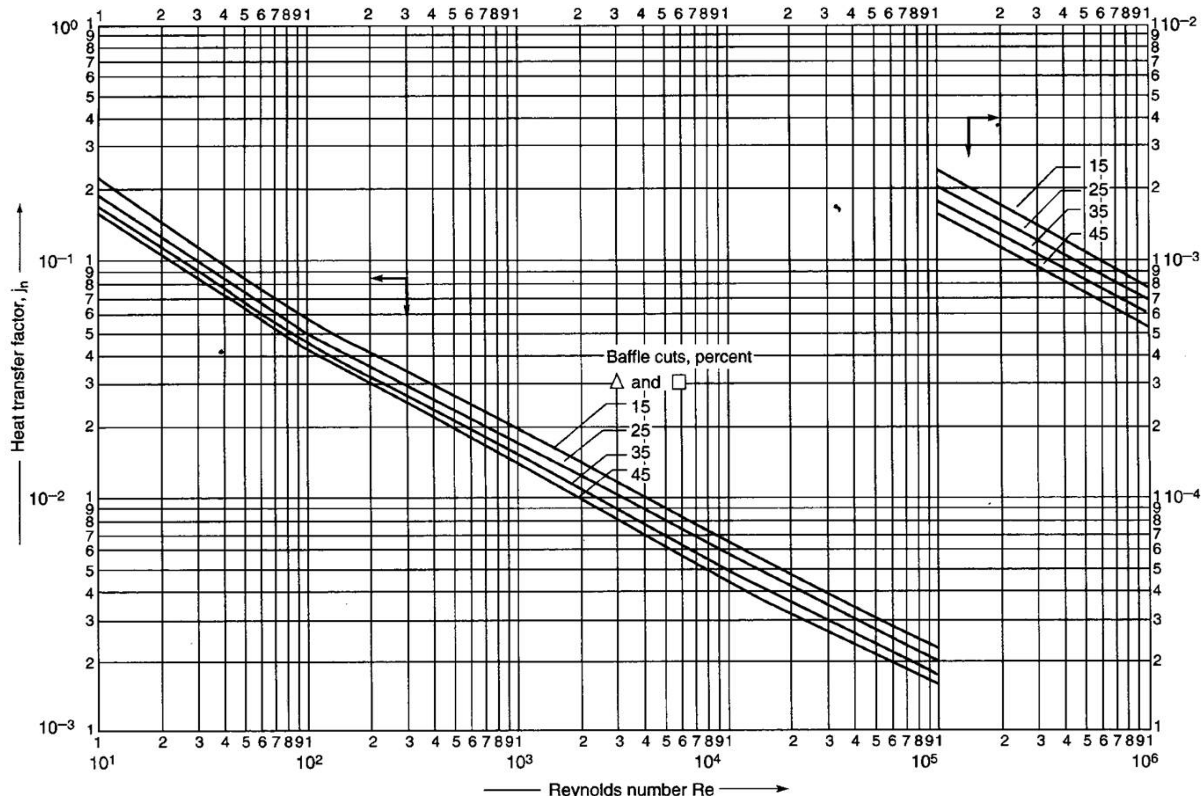

Figure 4: Shell side j_h factor.

7. Finally calculate Nu and obtain h_t by neglecting the viscosity correction term

$$\frac{h_s d_e}{k_f} =$$

$$=$$

$$=$$

So we get

$$h_s = \underline{\hspace{4cm}}$$

$$= \underline{\hspace{8cm}}$$

$$= \qquad W/m^2.^oC$$

4 Workbook: Calculation of the overall heat transfer coefficient

4.1 Problem statement

A heat exchanger is to be used to subcool condensate from a methanol condenser from 95^oC to 40^oC. Flow rate of methanol $100,000kg/h$. Brackish water will be used as the coolant, with a temperature rise from 25^oC to 40^oC.

Considering a 1-2 shell and tube heat exchanger, calculate the overall heat transfer coefficient.

4.2 Additional information

- Pipes to be used for the tube side has the specification: $3/4in$, $16ft$ that has the following dimensions
  $i.d. = 16mm$, $o.d. = 20mm$, $length = 4.88m$
- The conduction heat transfer coefficient of the wall is given by $k_w = 50W/m.^oC$

4.3 Analysis

- The overall heat transfer coefficient is given by

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o/d_i)}{2k_w} + \frac{1}{h_i}\frac{d_o}{d_i} + \frac{1}{h_{id}}\frac{d_o}{d_i}$$

- From the previous workbooks we got

$$h_i = 3910 w/m^2.^oC$$
$$h_o = 2740 w/m^2.^oC$$

- The value of the dirt coefficients can be obtained from the following table.

Table 12.2: Fouling Factors (Coefficients), Typical Values

Fluid	Coefficient (W/m^2 °C)	Factor (resistance) (m^2 °C/W)
River water	3000–12,000	0.0003–0.0001
Sea water	1000–3000	0.001–0.0003
Cooling water (towers)	3000–6000	0.0003–0.00017
Towns' water (soft)	3000–5000	0.0003–0.0002
Towns' water (hard)	1000–2000	0.001–0.0005
Steam condensate	1500–5000	0.00067–0.0002
Steam (oil free)	4000–10,000	0.0025–0.0001
Steam (oil traces)	2000–5000	0.0005–0.0002
Refrigerated brine	3000–5000	0.0003–0.0002
Air and industrial gases	5000–10,000	0.0002–0.0001
Flue gases	2000–5000	0.0005–0.0002
Organic vapors	5000	0.0002
Organic liquids	5000	0.0002
Light hydrocarbons	5000	0.0002
Heavy hydrocarbons	2000	0.0005
Boiling organics	2500	0.0004
Condensing organics	5000	0.0002
Heat transfer fluids	5000	0.0002
Aqueous salt solutions	3000–5000	0.0003–0.0002

4.4 Solution

- From the table, for brackish water, the heat transfer coefficient value of sea water is taken as and for methanol, that of organic liquid can be used.
- So we get,

$$h_{id} = 3000 W/m^2.^oC$$
$$h_{od} = 5000 W/m^2.^oC$$

- To get the overall heat transfer coefficient

$$\frac{1}{U_o} = = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o/d_i)}{2k_w} + \frac{1}{h_i}\frac{d_o}{d_i} + \frac{1}{h_{id}}\frac{d_o}{d_i}$$

$$=$$

$$=$$

- The value is significantly different from the assumed value. So the entire calculation needs to be repeated.

References

1. G. Towler and R. Sinnott. *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design*. Butterworth-Heinemann, 2008.