Experiment No: 8
Experiment Name: Extended Surface Heat Transfer- Unsteady State Heata Transfer

I. Extended Surface Heat Transfer

Aim of the experiment:

- To observe the temperature profiles and heat transfer characteristics for an extended surface (cylindrical pin) when heat flows along the rod by conduction and heat is lost along the rod by combined convection and radiation to the surroundings.
- To measure the temperature distribution along an extended surface and compare the result with a theoretical analysis.
- To calculate the heat transfer from an extended surface resulting from the combined modes of free convection and radiation heat transfer
- To determinine the thermal conductivity of the rod material.

Theory

Difficult heat exchange problems occur when one of the fluid streams has a much lower heat transfer coefficient than the other. Where it is required to cool a surface by convection, the rate of heat removal can be improved by increasing the area of the surface. This is usually achieved by adding extended surfaces called fins or pins. The use of fins or extended surfaces on the outside of a heat exchanger pipe wall to give relatively high heat transfer coefficients in the exchanger is quite common.

A temperature gradient exists along each fin or pin due to the combination of the conductivity of the material and heat loss to the surroundings (greater at the root and less at the tip).

The temperature distribution along the fin or pin must be known to determine the heat transfer from the surface to its surroundings. Since radiation and natural convection from the surface occur simultaneously, both of these effects must also be included in the analysis.

By considering the steady-state energy balance for an extended surface of uniform material and cross sectional area the following equation can be derived:

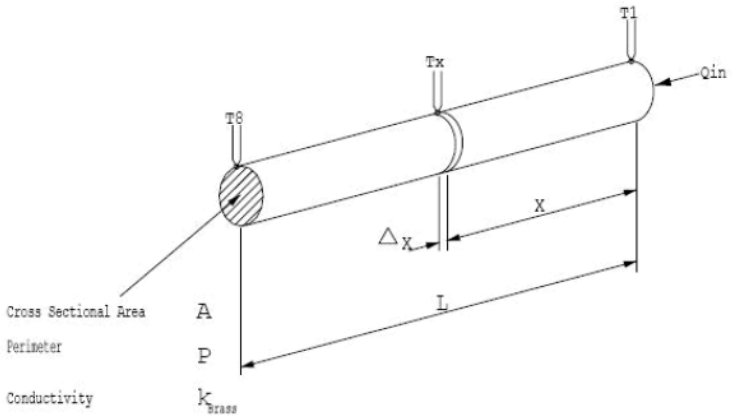
$$\frac{d^2\theta(x)}{dx^2} - m^2\theta(x) = 0$$

where

$$m^2 = \frac{(HP)}{(Ak_{Brass})} \qquad \theta(x) = Tx - Ta$$

Since H, P, A and k_{Brass} are constant for a given rod with fixed power input, m^2 must be constant and therefore m must be constant.

Assuming that the diameter of the pin is small in comparison with its length then heat loss at the tip can be assumed to be negligible (at the tip x = L).



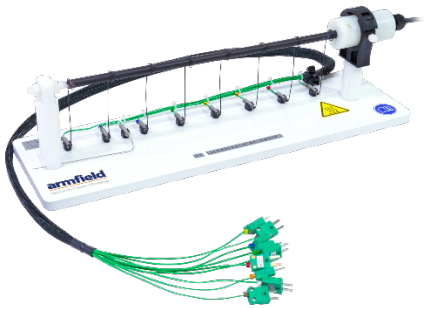
$$\frac{d\theta(x)}{dx} = 0 \quad \text{at} \quad x = L$$

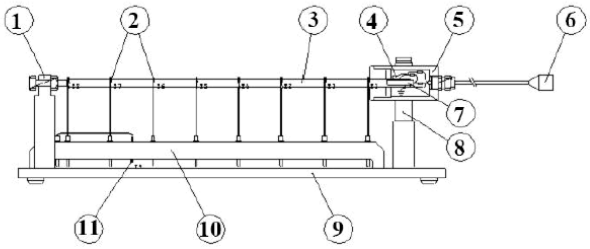
$$\frac{\theta(x)}{\theta_0} = \frac{Tx - Ta}{T1 - Ta} = \frac{\cosh m(L - x)}{\cosh m L}$$

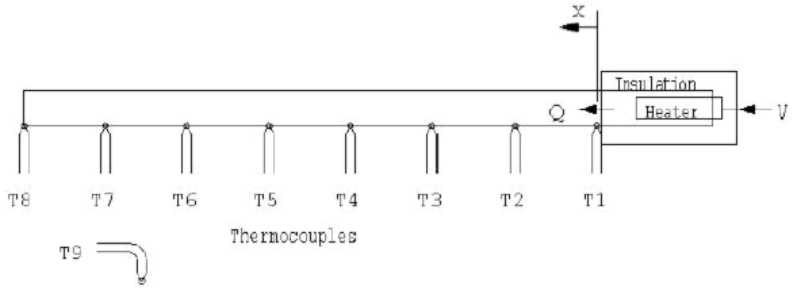
Equipment Setup

The long horizontal rod, which is heated at one end, provides an extended surface for heat transfer measurements. The bar (3) is manufactured from a solid cylindrical brass bar with a constant diameter of 10mm and is mounted horizontally with a support (8) at the heated end and a steady (1) at the tip. Thermocouples at regular intervals along the rod allow the surface temperature profile to be measured. Eight thermocouples (2) are attached to the surface of the rod at equal intervals of 50 mm giving an overall instrumented length of 350 mm. By making the diameter of the rod small in relation to its length, thermal conduction along the rod can be assumed to be one-dimensional and heat loss from the tip can be ignored.

The rod is heated by a cartridge type electric heating element (7).







Name	Symbol	Unit
Voltage to heater	V	V
Current to heater	I	A
Power supplied to heater	Qin	W
Diameter of extended surface	D	m
Length of extended surface	L	m
Heat transfer area	As	m^2
Cross sectional area	A	m^2
Distance along the extended surface (from T1)	x	m
Thermal conductivity of extended surface	k_{Brass}	$Wm^{-1}K^{-1}$
Total heat loss from extended surface	Qtot	W
Overall heat transfer coefficient	H	$Wm^{-2}K^{-1}$
Heat transfer coefficient for natural convection	Hc	$Wm^{-2}K^{-1}$
Heat transfer coefficient for radiation	Hr	$Wm^{-2}K^{-1}$
Stefan Boltzmann constant	σ (= 56.7 x 10^{-8})	$Wm^{-2}K^{-4}$
Emissivity of surface	ε	Dimensionless
Area factor (geometric factor)	F	Dimensionless
Average temperature of extended surface	Tav	°C
Average temperature of extended surface	Ts (=Tav + 273)	K
Temperature of ambient air/surroundings	T9	°C
Temperature of ambient air/surroundings	Ta (=T9 + 273)	K
Film temperature of air	T_{film}	K
Constant	m	m^{-1}

Procedure

- Switch on the front Mains switch.
- Set the heater voltage to 20 Volts.

- Monitor temperature T_1 regularly. When T_1 reaches 80°C reduce the heater voltage to 9 Volts.
- When the temperatures are stable record the following.
- T_1- T_9, V, I
- Repeat the readings at different heater voltage values.

Results

For this exercise:

Heater Voltage: V Volts

Heater Current: I Amps

Temperature at heated end where x = 0 T_1 (°C)

Temperature at x = 0.05m T_2 (°C)

Temperature at x = 0.10m T_3 (°C)

Temperature at x = 0.15m T_4 (°C)

Temperature at x = 0.20m T_5 (°C)

Temperature at x = 0.25m T_6 (°C)

Temperature at x = 0.30m T_7 (°C)

Temperature at tip where x = 0.35m T_8 (°C)

Temperature of ambient air T_9 (°C)

Heat flow (Power to heater) Q_{in} = (Watts)

Average surface temperature of the rod T_s = (K)

Ambient temperature T_a = (K)

Heat transfer area (surface area) A_s = (m^2)

Heat transfer coefficient (natural convection) H_{cm} = ($Wm^{-2}K^{-1}$)

Heat transfer coefficient (radiation) H_{rm} = ($Wm^{-2}K^{-1}$)

Overall heat transfer coefficient H = ($Wm^{-2}K^{-1}$)

Total heat transferred to surroundings Q_{tot} = (W)

Length of rod = 0.35 (m). Diameter of rod D = 0.01 (m). The distance between each thermocouple is 0.05m.

For each position along the rod (dimension x) use the corresponding measured temperatures to find the value of m which satisfies the relationship:

$$\frac{Tx - T9}{T1 - T9} = \frac{\cosh m(L - x)}{\cosh m L}$$

The value for m can be found by iteration using a suggested starting value of 7.4.

Find the average value of m then use this value to calculate the theoretical temperature T_x at each position x along the rod.

Repeat this procedure for each set of temperature readings obtained and confirm that for each set of readings the value for m remains constant.

Plot a graph of measured *surface temperature* T_x and calculated *surface temperature* T'_x against position x.

$Q_{tot} = H A_s (T_s - T_a)$

$H = H_{cm} + H_{rm}$

$$Hc_m = 1.32\left[\frac{(Ts - Ta)}{D}\right]^{0.25}$$

$$Hr_m = \sigma\xi F\frac{(Ts^4 - Ta^4)}{(Ts - Ta)}$$

σ= Stefan Boltzmann constant, 56.7 x 10^{-9} ($Wm^{-2}K^{-4}$)
ξ = Emissivity of surface, 0.95 (Dimensionless)
F = View factor, 1 (Dimensionless)

Calculate k_{Brass}

$$m^2 = \frac{HP}{k_{Brass}A}$$

Where,
H = Overall heat transfer coefficient due convection and radiation ($Wm^{-2}K^{-1}$)
P = Perimeter of the pin
A = Cross sectional area of the pin

Discussion

- What was the effect of varying the heater power?
- Compare the measured power Q_{in} to the heater with the calculated heat loss Q_{tot} from the rod.
- Estimate the cumulative influence of the experimental errors on your calculated values for Ts, T_a, H_r, H_c, H, P, A_s, A, m and k_{Brass} and measured values for x, L, D, T_1 to T_9, V, and I.

II. Unsteady State Heat Transfer

Aim of the experiment:

- To observe unsteady state conduction of heat to the centre of a solid shape when a step change is applied to the temperature at the surface of the shape.
- To determine the thermal conductivity constant of the disk material using analytical transient-temperature/heat flow charts

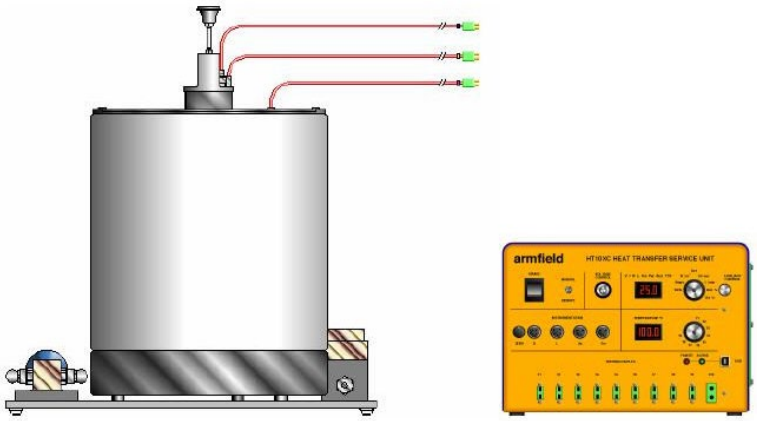
Theory

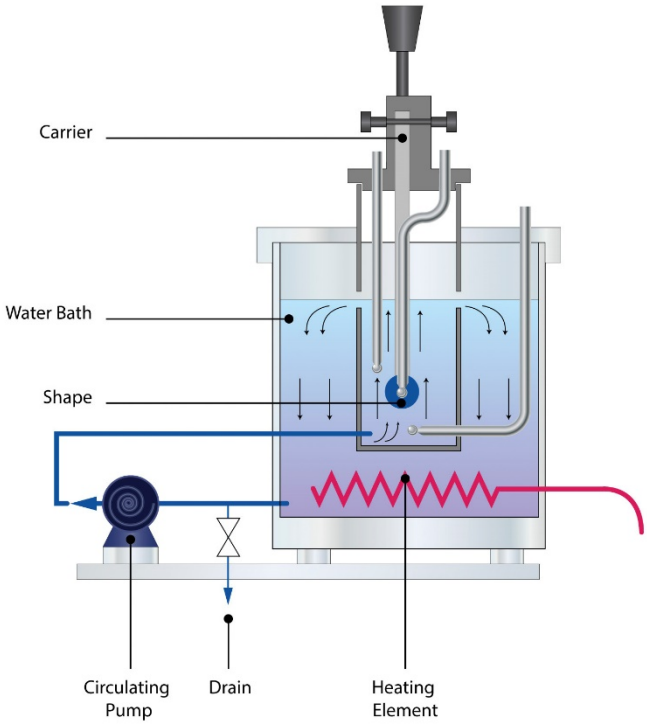
When a solid shape is immersed in hot water and continues until the whole of the shape reaches equilibrium with the temperature of the water.

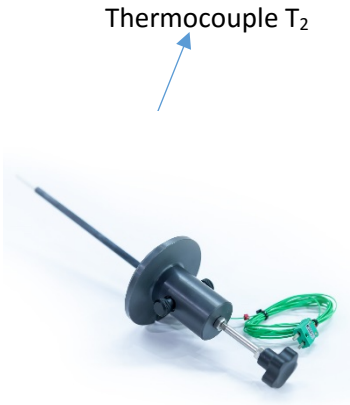
When the step change is applied a temperature gradient exists between the surface of the shape at the water temperature and the centre of the shape which is at ambient temperature. Heat flows by conduction through the shape until the whole of the shape is at the same temperature as the water. Analytical solutions are available for temperature distribution and heat flow as a function of time and position for simple solid shapes which are suddenly subjected to convection with a fluid at a constant temperature.

Equipment Setup

The equipment consists of a heated water bath together with set of instrumented shaped test pieces. Each of the shapes incorporates a thermocouple to measure the temperature at the centre of the shape. Each of the shapes is attached to a holder while measurements are taken. Solid shapes of different size, form and material of construction are allowed to
stabilise at room temperature then dropped into a bath of hot water.







Seven solid shapes are manufactured in three simple shapes and two materials. Each of the shapes incorporates a thermocouple to measure the temperature at the centre of the shape.

Small cylinder 20mm diameter x 100mm long manufactured in Brass

Large cylinder 30mm diameter x 100mm long manufactured in Brass

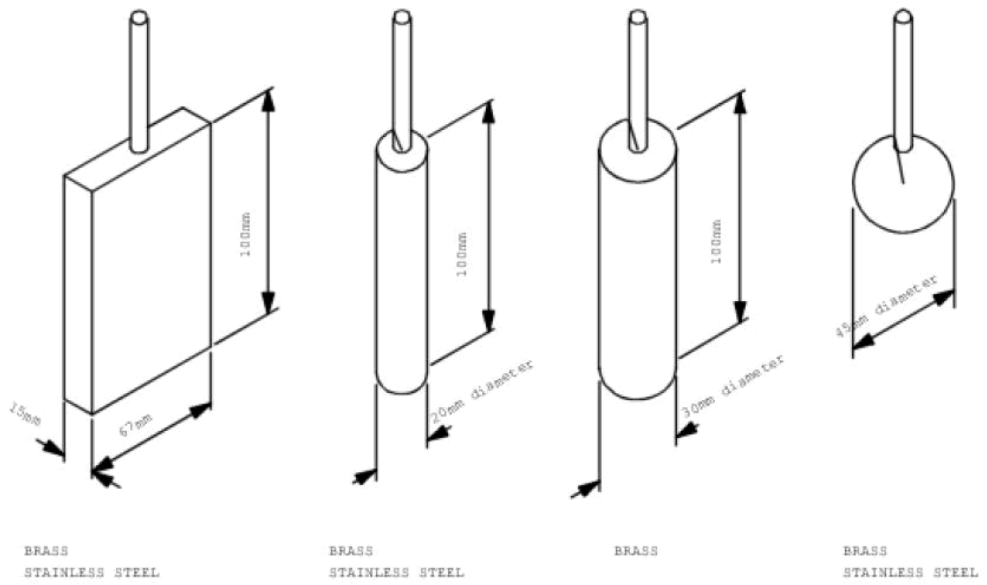
Small cylinder 20mm diameter x 100mm long manufactured in Stainless Steel

Sphere 45mm diameter manufactured in Brass

Sphere 45mm diameter manufactured in Stainless Steel

Rectangular slab 70mm x 15mm x 76mm long manufactured in Brass

Rectangular slab 70mm x 15mm x 76mm long manufactured in Stainless Steel



Thermocouple T_1 is located inside the water bath, allows the temperature of the water to be monitored and adjusted to the required temperature before immersing the shapes.
Thermocouple T_2 mounted on the shape holder contacts the hot water at the same instant as the solid shape and provides an accurate datum for temperature/time measurements.
Thermocouple T_3 is installed permanently inside each of the solid shapes.

Monitoring of the temperature at the centre of the shape allows analysis of heat flow using the appropriate transient-temperature/heat-flow charts provided.

Procedure

- Check that the water heater is filled with water.
- Connect the power lead from the water bath to an electrical supply (Since the water bath will take approximately 40 minute to heat to the required temperature it is suggested that this is switched on before the experiment).
- Ensure that the service unit is connected to an electrical supply.
- Adjust the thermostat on the water heater to setting '4' and check that the red light is illuminated indicating that power is connected to the heating element.
- Allow each shape to stabilise at room temperature. Always pick up the metal shapes via the insulated rod.
- Connect thermocouple T_1 from the flow duct inside the water bath to socket T_1; thermocouple T_2 on the shape holder to socket T_2; thermocouple T3 inside the large brass shape to socket T_3 on the front of the service unit.

- Set the voltage to the circulating pump to 12 Volts.
- Allow the temperature of the water (T_1) to stabilise. The water must be in the range 80-90°C for satisfactory operation.
- Attach the solid shape to the shape holder (insert the insulated rod into the holder and secure using the transverse pin) but do not hold the metal shape or subject it to a change in temperature.
- Check that the temperature of the shape has stabilised (T_2).
- Switch off the electrical supply to the water bath to minimise fluctuations in temperature if the thermostat switches on/off.
- Start to record temperatures T_1, T_2 and T_3.
- Allow the temperature of the shape to stabilise at the hot water temperature (T_3).
- Remove the solid shape from the shape holder and then fit another shape and repeat the above procedure.

Name	Symbol	Unit
Voltage to circulating pump	V	V
Current to circulating pump	I	A
Temperature of water in heated bath	T1	°C
Temperature of air/water (shape holder)	T2	°C
Temperature at centre of shape	T3	°C
Temperature	θ	dimensionless
Biot number	Bi	dimensionless
Fourier number	τ	dimensionless time
Radial co-ordinate (for cylinder or sphere)	R	dimensionless
Linear co-ordinate (for slab)	X	dimensionless
Thermal diffusivity of the shape	α	(m^2s^{-1})
Heat transfer coefficient (water to shape)	h	($Wm^{-2}°C^{-1}$)
Thermal conductivity of the shape	k	($Wm^{-1}°C^{-1}$)
Time since step change	t	(seconds)
Temperature at centre of shape (=T3 at time t)	T(0,t)	(°C)
Initial temperature of shape (= T3 at t=0)	TI	(°C)
Temperature of water bath (= T1)	T_∞	(°C)
Radius of cylinder or sphere	b	(m)

Results

Plot T_1, T_2 and T_3 vs. time.

Analytical solutions are available for temperature distribution and heat flow as a function of time and position for simple solid shapes which are suddenly subjected to convection with a fluid at a constant temperature. The charts are given in Appendix.

To use the charts it is necessary to evaluate appropriate dimensionless parameters as follows:

$$\theta = \frac{T(r,t) - T_\infty}{T_i - T_\infty} = \text{dimensionless temperature}$$

$$Bi = \frac{hb}{k} = \text{Biot number}$$

$$\tau = \frac{\alpha t}{b^2} = \text{dimensionless time or Fourier number}$$

where

α = Thermal diffusivity of the cylinder (m^2s^{-1})

h = Heat transfer coefficient ($Wm^{-2}{}^\circ C^{-1}$)

k = Thermal conductivity of the cylinder ($Wm^{-1}{}^\circ C^{-1}$)

t = Time since step change (seconds)

T(0,t) = Temperature at centre of cylinder (=T3 at time t) (°C)

T_i = Initial temperature of cylinder (T3 at t=0) (°C)

T_∞ = Temperature of water bath (T1) (°C)

b= Radius of cylinder (m)

r= radial position within the cylinder (at axis r=0) (m)

For a solid slab:

$$Bi = \frac{hL}{k} = \text{Biot number}$$

$$\tau = \frac{\alpha t}{L^2} = \text{Fourier number (dimensionless time)}$$

L =0.5x thickness of slab (m)

For solid sphere

$$Bi = \frac{hb}{k} = \text{Biot number for slab}$$

$$\tau = \frac{\alpha t}{b^2} = \text{Fourier number (dimensionless time)}$$

b = Radius of sphere (m)

Since the flow of water vertically upwards through the duct is constant for all of the measurements, the heat transfer coefficient h will remain constant for each shape.

Choose a point on the temperature/time plot for the brass cylinder and measure the corresponding values of temperature T_3 and time t. (the point should be close to the final temperature e.g. 2 or 3 degrees away from the final temperature).

Calculate θ knowing Ti (T_3 at t=0), and T_3 ie. T(r=0, t)

Calculate τ knowing α, t and b (assume $\alpha = 3.7 \times 10^{-5}$ m^2s^{-1} for brass; $\alpha = 0.6 \times 10^{-5}$ m^2s^{-1} for stainless steel)

Read value for 1/Bi on chart using the calculated values for τ and θ

Calculate h knowing Bi, b and k (assume k = 121 Wm^{-1} $^oC^{-1}$ for brass; k = 25 Wm^{-1} $^oC^{-1}$ for stainless steel)

Discussion

- Observe how, in a solid shape, temperature changes with time.
- The time taken for the temperature to stabilise at the centre of the shape depends on the size, form and the material of the solid shape. Discuss the results and reasons for each shape.
- Discuss how h varies with the solid shape size, material.

REFERENCES:

- Armfield HTC11 & HTC 12 Instruction manual
- Transport Processes and Separation Process Principles (Includes Unit Operations): Christie John Geankoplis
- Unit Operations of Chemical Engineering, 7th Edition by Warren McCabe and Julian Smith and Peter Harriott

APPENDIX

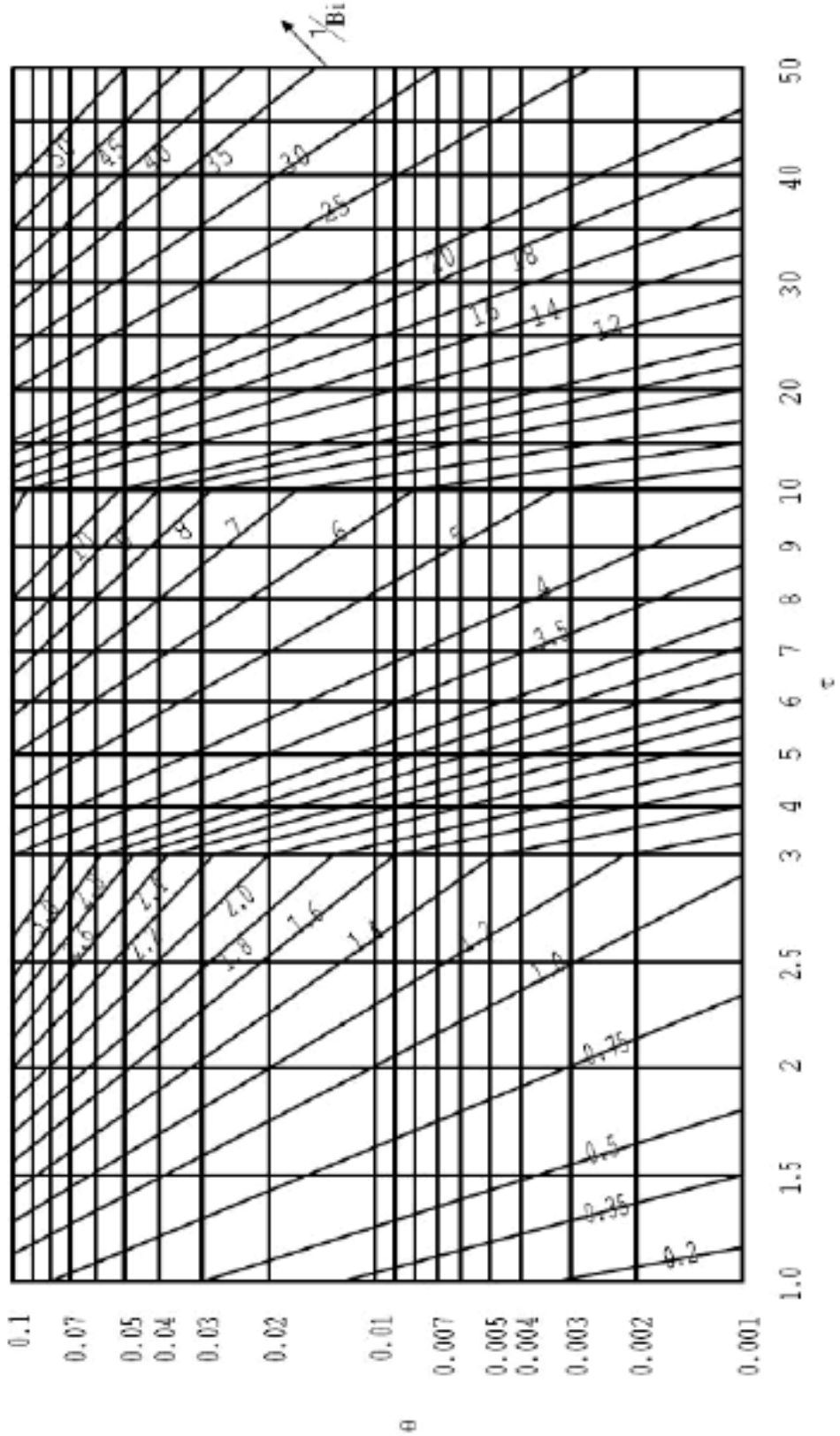


CHART FOR SOLID SPHERE

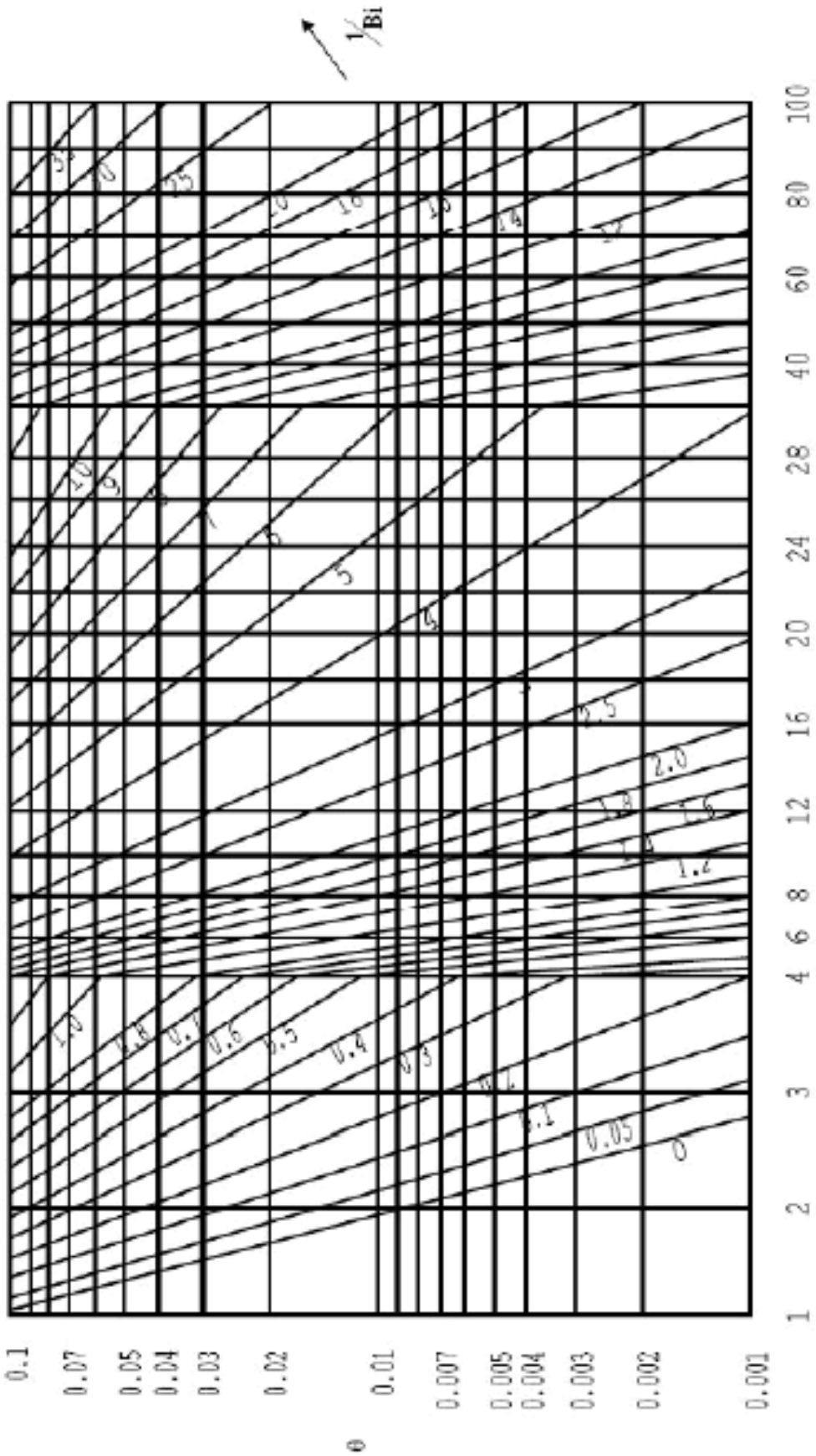


CHART FOR SOLID SLAB

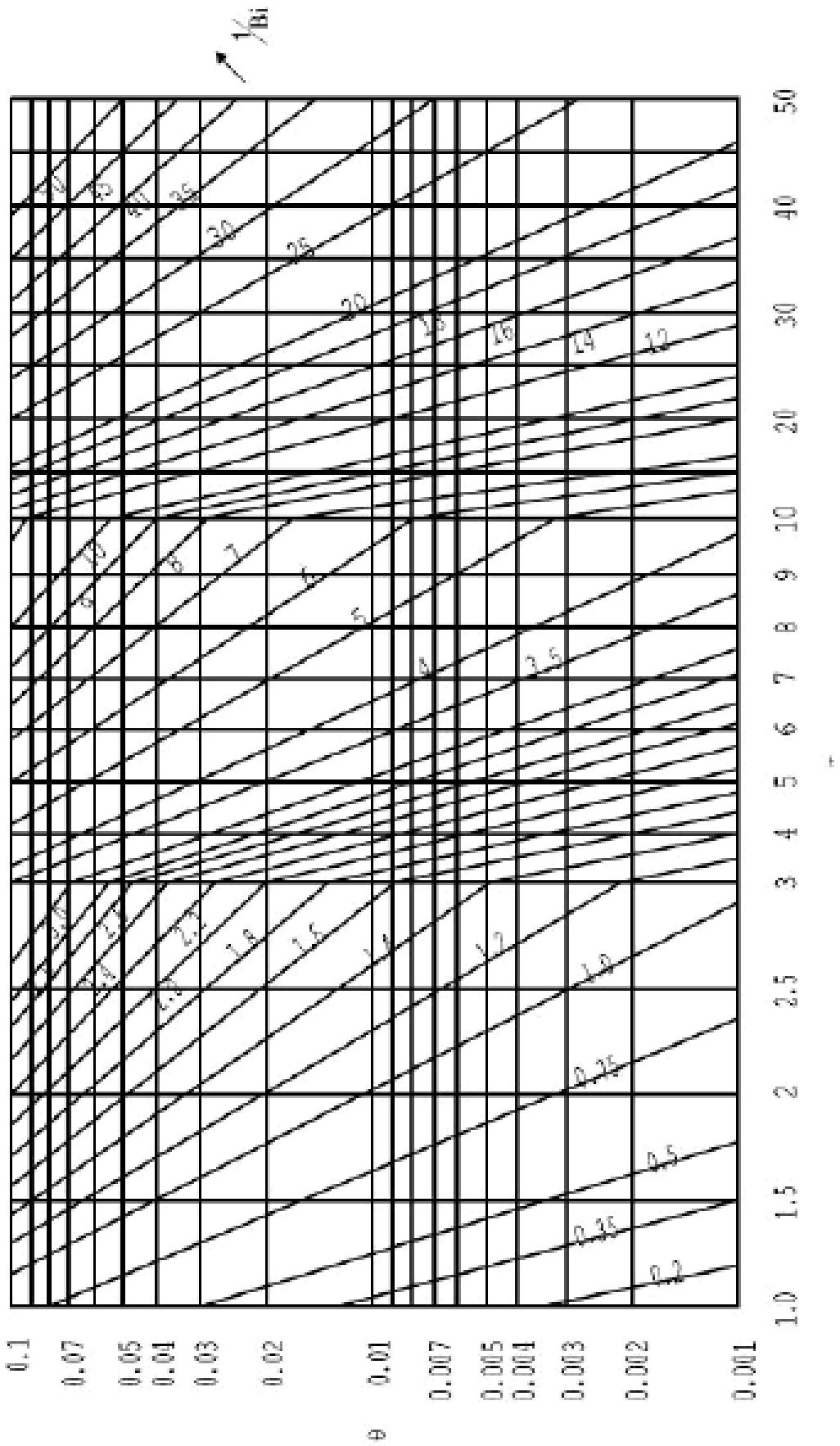


CHART FOR LONG CYLINDER