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Forced convection heat transfer in straight tubes Part 2. laminar and transitional flow

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FORCED CONVECTION HEAT TRANSFER IN STRAIGHT TUBES

PART 2: LAMINAR AND TRANSITIONAL FLOW

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FORCED CONVECTION HEAT TRANSFER IN STRAIGHT TUBES

PART 2: LAMINAR AND TRANSITIONAL FLOW

1. NOTATION AND UNITS

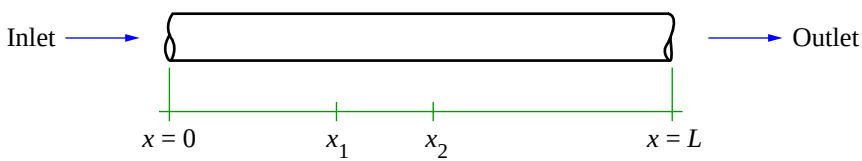
		<i>Units</i>	
		<i>SI</i>	<i>British</i>
A	heat transfer area of tube internal surface, $\pi D x$	m^2	ft^2
c_p	specific heat capacity at constant pressure	J/kg K	$\text{Btu/lb } ^\circ\text{F}$
D	tube internal diameter	m	ft
F_2	parameter defined in Appendix A	—	—
g	acceleration due to gravity	m/s^2 (9.81)	ft/h^2 (4.17×10^8)
Gr	Grashof number, see Section 3.5	—	—
Gz	Graetz number, $\dot{M} c_p / \lambda x$	—	—
L	tube length	m	ft
L_h	hydrodynamic entry length	m	ft
L_t	thermal entry length	m	ft
$\dot{m}$	mass flux	kg/s m^2	lb/h ft^2
$\dot{M}$	total mass flow rate per tube	kg/s	lb/h
Nu	Nusselt number, $\alpha D / \lambda$	—	—
Pr	Prandtl number, $c_p \eta / \lambda$	—	—
$\dot{q}$	local heat flux	W/m^2	$\text{Btu/ft}^2 \text{ h}$
$\dot{Q}$	total heat duty	W	Btu/h
r	radial co-ordinate	m	ft
Re	Reynolds number, $\dot{m} D / \eta$	—	—
S	tube cross-sectional area, $\pi D^2 / 4$	m^2	ft^2
T	temperature	K	$^{\circ}\text{R} (\approx ^\circ\text{F} + 460)$

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u	local fluid velocity in axial direction	m/s	ft/h
V	mean fluid velocity in axial direction	m/s	ft/h
x	axial or streamwise co-ordinate	m	ft
α	heat transfer coefficient	W/m ² K	Btu/ft ² h °F
β	coefficient of volumetric expansion	1/K	1/°F
η	dynamic viscosity	kg/m s	lb/ft h
λ	thermal conductivity	W/m K	Btu/h ft °F
ρ	density	kg/m ³	lb/ft ³

Subscripts

$a m$	arithmetic mean value
b	bulk fluid value
c	constant fluid property value
H	uniform heat flux thermal boundary condition
i	inlet conditions
l	laminar flow
$l m$	logarithmic mean value
m	mean value over axial distance
o	outlet conditions
t	turbulent flow
T	uniform wall temperature thermal boundary condition
w	conditions at wall
x	local value at axial position x



Sketch 1.1 Axial co-ordinate notation

2. INTRODUCTION

This Data Item is the second of two on forced convection heat transfer in straight tubes, and supersedes ESDU 68006. Methods are presented for the prediction of heat transfer in straight tubes for forced laminar and transitional flows and for mixed laminar convection.

As a companion to ESDU 92003 some of the methods presented here require the use of data presented in ESDU 92003 (in particular the flow regime maps of Figures 3 and 4).

Section 3 provides definitions of the bulk fluid temperature, the heat transfer coefficient, Nusselt number, Graetz number and Grashof number. The results of the analysis of laminar flow heat transfer and empirical equations for the estimation of Nusselt numbers are presented in Section 4. Methods of accounting for other factors – variable fluid properties and buoyancy – which influence laminar flow heat transfer are presented in Section 5 and in Section 6 an equation is recommended for the prediction of heat transfer in the transition flow region. The use of the data is illustrated by the worked examples of Section 7.

3. DEFINITIONS

3.1 Bulk Fluid Temperature

The local value of the fluid temperature T is a function of axial position, x , and radial position, r . To achieve a simple representation of the heat transfer a characteristic temperature of the fluid, namely the local bulk fluid temperature, $T_{b,x}$, is defined at axial position x .

$$\dot{m} c_{p,b,x} T_{b,x} = \frac{1}{S} \int_S \rho c_p u T \, dS. \quad (3.1)$$

This definition is difficult to use unless the specific heat capacity, c_p , is assumed to be constant over the tube cross-section. The definition of the local bulk fluid temperature, $T_{b,x}$, then simplifies to

$$T_{b,x} = \frac{1}{\dot{m} S} \int_S \rho u T \, dS. \quad (3.2)$$

The variation of the local bulk temperature along the tube is related to the local wall heat flux. Between any two axial stations x_1 and x_2 the change in local bulk temperature is given by

$$T_{b,x_2} - T_{b,x_1} = \frac{\pi D}{\dot{M}} \int_{x_1}^{x_2} \frac{\dot{q}}{c_p} \, dx. \quad (3.3)$$

When the specific heat capacity is assumed to be constant between the two axial stations the change in the local bulk temperature simplifies to

$$T_{b,x_2} - T_{b,x_1} = \frac{\pi D}{\dot{M} c_p} \int_{x_1}^{x_2} \dot{q} \, dx. \quad (3.4)$$

The mean bulk temperature between two axial stations along the tube is given by

$$T_{b,m} = \frac{T_{b,x_1} + T_{b,x_2}}{2} . \quad (3.5)$$

3.2 Heat Transfer Coefficients

The heat transfer between the tube wall and a fluid moving relative to the wall can be expressed in terms of a local heat transfer coefficient defined as

$$\alpha_x = \frac{\dot{q}}{|T_w - T_b|_x} . \quad (3.6)$$

The definition of the flow-length mean heat transfer coefficient consistent with Equation (3.6) is

$$\alpha_m = \frac{1}{L} \int_0^L \alpha_x \, dx . \quad (3.7)$$

In practice, it is usually more convenient to use a mean heat transfer coefficient defined in terms of the total heat load over the entire tube and a characteristic mean temperature difference. There are two tube wall thermal boundary conditions for which the definition is relatively simple.

The first is the uniform heat flux (UHF) thermal boundary condition for which the mean heat transfer coefficient, α_{am} , is based on the arithmetic mean temperature difference (AMTD).

$$\alpha_{am} = \frac{\dot{Q}/A}{\Delta T_{am}} , \quad (3.8)$$

where
$$\Delta T_{am} = \frac{(T_w - T_b)_i + (T_w - T_b)_o}{2} . \quad (3.9)$$

The second thermal boundary condition is the uniform wall temperature (UWT) thermal boundary condition for which the mean heat transfer coefficient, α_{lm} , is based on the logarithmic mean temperature difference (LMTD).

$$\alpha_{am} = \frac{\dot{Q}/A}{\Delta T_{lm}} , \quad (3.10)$$

where
$$\Delta T_{lm} = \frac{(T_w - T_{b,i}) + (T_w - T_{b,o})}{\log_e \left[\frac{(T_w - T_{b,i})}{(T_w - T_{b,o})} \right]} . \quad (3.11)$$

These conditions are closely approached in practice in a number of situations.

The UWT thermal boundary condition is closely approached when the outside tube surface is heated by an isothermally condensing fluid, or cooled by an isothermally boiling fluid. It is also approached in a number of other situations, such as in co-current (parallel) heat exchangers where the heat transfer coefficient and

flowing heat capacity ($\dot{M}c_p$) for the external flow are approximately equal to the corresponding values for the flow inside the tubes, or in heat exchangers where the heat transfer coefficient and flowing heat capacity ($\dot{M}c_p$) for the external flow are much larger than the corresponding values for the laminar flow inside the tubes.

The UHF thermal boundary condition solutions are generally applied to the practical situations of electric resistance heating and counter-current heat exchangers where the values of heat transfer coefficient and flowing heat capacity ($\dot{M}c_p$) for the shell-side are approximately equal to the corresponding values for the flow in the tubes.

The influence of the thermal boundary condition is significant in laminar flow and in Section 4, correlations for heat transfer in laminar flow are given for the UHF and UWT thermal boundary conditions.

When the thermal boundary conditions do not correspond to either the UHF or the UWT boundary condition it is recommended that the UWT correlations be used, but with the relationship for the mean temperature difference amended to the following

$$\Delta T_{lm} = \frac{(T_w - T_b)_i + (T_w - T_b)_o}{\log_e \left[\frac{(T_w - T_b)_i}{(T_w - T_b)_o} \right]}. \quad (3.12)$$

This represents an approximation and when there is concern about the accuracy of the constant wall temperature assumption the tube should be treated as a series of short sections for which the boundary conditions are known.

3.3 Nusselt Number

The local Nusselt number is defined as

$$Nu_x = \frac{\alpha_x D}{\lambda} \quad (3.13)$$

and the mean Nusselt number is defined as

$$Nu_m = \frac{\alpha_m D}{\lambda}. \quad (3.14)$$

3.4 Graetz Number

There are a number of definitions of the Graetz number in the literature, all of which are simply related. The definition of the Graetz number used in this Item is

$$Gz = \frac{\dot{M}c_p}{\lambda x} = \frac{\pi}{4} Re Pr \frac{D}{x}. \quad (3.15)$$

3.5 Grashof Number

The Grashof number is defined as

$$Gr = \frac{\beta g D^3 \rho^2 |\Delta T|}{\eta^2}, \quad (3.16)$$

where ΔT is some characteristic temperature difference. Equations (5.2) and (5.3) of this Item use the following definition of the Grashof number:

$$Gr_w = \frac{\beta g D^3 \rho_w^2 |T_w - T_{b,i}|}{\eta_w^2} \quad (3.17)$$

and Equation (5.5) uses the definition

$$Gr_b = \frac{\beta_b g D^3 \rho_b^2 |\Delta T_{am}|}{\eta_b^2}. \quad (3.18)$$

3.6 Evaluation of Fluid Properties

Except where stated otherwise the data for the calculation of local heat transfer coefficients apply for fluid properties evaluated at the bulk temperature, T_b , at any axial position along the tube and the data for the calculation of the mean heat transfer coefficient apply for fluid properties evaluated at the mean bulk temperature, $T_{b,m}$, between the two axial stations along the tube.

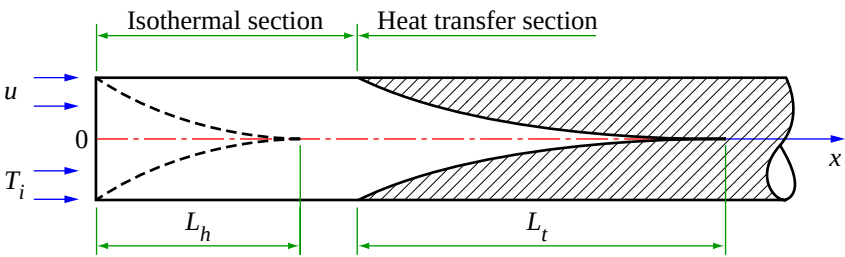
3.7 Hydrodynamic and Thermal Entry Lengths

The hydrodynamic entrance length, L_h , is defined as the axial distance required to attain 99% of the fully-developed maximum velocity from a uniform velocity profile at inlet (Derivation 23).

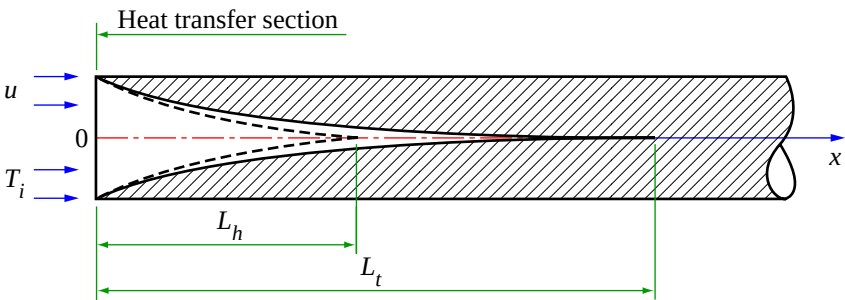
The Nusselt number is highest at the point of commencement of heating and diminishes to a constant value when fully-developed flow is established. The thermal entrance length L_t is therefore defined as the axial distance required from the point of commencement of heating for the local Nusselt number to attain a value 1.05 times the fully-developed flow value (Derivation 23).

Sketches 3.1 and 3.2 illustrate the flow development for thermally-developing flow and simultaneously-developing flow*. In the case of thermally-developing flow the heat transfer commences downstream of an isothermal section of sufficient length for the velocity profile to become established, whereas, in the case of simultaneously-developing flow, heat transfer commences at the tube inlet.

* Throughout this Data Item 'thermally-developing flow' refers to thermally-developing and hydrodynamically-developed flow. 'Simultaneously-developing flow' refers to thermally- and hydrodynamically-developing flow. These descriptions are taken from Derivations 21 and 23.



Sketch 3.1 Hydrodynamic and thermal entry lengths for thermally-developing flow



Sketch 3.2 Hydrodynamic and thermal entry lengths for simultaneously-developing flow