



CFD Benchmarks for predicting friction losses and flow characteristics in straight pipes

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THE PREPARATION OF THIS CFD GUIDE

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CFD BENCHMARKS FOR PREDICTING FRICTION LOSSES AND FLOW CHARACTERISTICS IN STRAIGHT PIPES

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CFD BENCHMARKS FOR PREDICTING FRICTION LOSSES AND FLOW CHARACTERISTICS IN STRAIGHT PIPES

1. PURPOSE AND SCOPE OF THIS CFD GUIDE

The purpose of this CFD Guide is to provide reliable benchmark data for the validation of CFD predictions in straight pipes in incompressible flow. Input geometrical and flow parameters for circular straight pipes with smooth walls in laminar to turbulent flow are provided for defining two CFD Benchmarks. Comparisons of the benchmark data with ESDU CFD predictions performed using the validation methodology described in ESDU TN 08008⁴⁸ and ESDU TN 08009⁴⁹ are discussed in detail.

2. NOTATION AND UNITS

		SI Unit
A	pipe cross-sectional area	m^2
D	pipe internal diameter	m
f	friction factor, defined in Equation (5.1), also termed Fanning friction factor	–
K_{en}	non-dimensional additional entrance pressure drop, defined in Equation (5.9) and Sketch 5.2	–
L	pipe length	m
L_d	pipe length required to reach fully-developed flow conditions	m
m	mass flow rate	kg/s
p	static pressure	Pa
R	pipe internal radius	m
Re	pipe Reynolds number, defined as $Re = u_{mean} D/\nu$	–
Re_θ	momentum-thickness Reynolds number, defined as $Re_\theta = \theta u_\infty/\nu$	–
r	pipe radial coordinate	m
u	axial local velocity in laminar flow or time-mean axial local velocity in turbulent flow	m/s
u^+	non-dimensional local axial velocity, defined as $u^+ = u / u_\tau$	m/s
u_{cl}	axial local centre-line velocity	m/s
$u_{cl,fd}$	axial centre-line velocity in fully-developed flow conditions	m/s
u_{mean}	bulk-mean velocity, defined as $u_{mean} = m/(A\rho)$	m/s
u_τ	friction velocity, defined as $u_\tau = \sqrt{\tau_w / \rho}$	m/s
u_∞	local free-stream velocity	m/s

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x	pipe axial coordinate	m
Y_{plus}	wall y^+ , defined as $Y_{plus} = y_w u_\tau / \nu$	–
y	distance from wall	m
y_w	distance from wall of closest mesh node	m
y^+	non-dimensional wall distance, defined as $y^+ = y u_\tau / \nu$	–
Δp_{en}	additional pipe pressure drop due to entry of fluid into pipe from a large tank, defined in Sketch 5.2	Pa
$\Delta p_{en,tot}$	pressure drop between pipe entrance and fully-developed flow axial location, defined in Sketch 5.2	Pa
γ	intermittency factor, defined as the fraction of time that motion is turbulent in the transition process	–
κ	turbulence kinetic energy	m^2/s^2
ε	turbulence eddy dissipation	m^2/s^3
λ	alternative friction factor, defined as $\lambda = 4f$	–
μ	fluid dynamic viscosity	Pa s
ν	fluid kinematic viscosity	m^2/s
θ	boundary-layer momentum thickness	m
ρ	fluid density	kg/m^3
τ	fluid shear stress	Pa
τ_w	wall fluid shear stress	Pa
ω	turbulent frequency	s^{-1}

Abbreviations Glossary

AUTOMATIC	ANSYS CFX proprietary near-wall treatment which switches automatically from wall-functions to a low-Reynolds-number treatment near-wall formulation as the mesh is refined
CFD	computational fluid dynamics
DNS	direct numerical simulation
LDA	laser Doppler anemometry
LES	large eddy simulation
RANS	Reynolds-averaged Navier Stokes
SCALABLE	ANSYS CFX proprietary near-wall treatment which allows solution on arbitrarily fine mesh near the wall when using the $\kappa - \varepsilon$ turbulence model
SST	shear stress transport

3. INTRODUCTION

ESDU CFD-BMK 09011 provides the CFD Benchmarks recommended by ESDU for the validation of the predictions for friction losses and flow characteristics in circular straight pipes with smooth walls. These benchmarks can be used for industrial pipe-flow applications where pipes are part of more complex equipment, such as aircraft ducts, pipe fittings, heat exchangers, various components of power generation plants, *etc.* They may also be used in more general CFD applications where straight pipes are used to set inlet and outlet boundary conditions. At inlet boundaries, they can be used to set the length of the artificial inlet extension required for a natural development of duct boundary layers. At outlet boundaries, these benchmarks may be used to set the length of the artificial outlet extension required to reduce the influence of the outlet local fluid dynamics on the overall CFD predictions.

Accurate prediction of the friction losses and flow characteristics in straight pipes is one of the most challenging problems in CFD. Although direct numerical simulation (DNS) and large eddy simulation (LES) are used in research, in industry Reynolds-averaged Navier-Stokes (RANS) methods are largely used.

The benchmark data presented here are based on reliable measurements, DNS simulations and correlations from

- the published literature (References 1, 4, 9, 11, 12, 14-45), and
- Private Communications (References 46 and 47).

Two CFD Benchmarks are presented that cover the flow conditions and Reynolds numbers summarised in Table 3.1.

TABLE 3.1 Summary of the CFD Benchmarks for flow in straight pipes

Benchmark	Flow condition	Pipe Reynolds number	Type of data
1	Fully-developed	10 to 10^7	Measurements, DNS and correlations
2	Pipe Entrance	10 to 10^7	Measurements and correlations

Comparisons with the ESDU validated CFD predictions are presented. These were performed using the following assumptions:

- straight circular pipes with smooth walls,
- laminar, transitional and turbulent flow regimes,
- swirl-free, uniform inlet velocity conditions,
- fully-developed exit flow conditions,
- steady-state flow conditions,
- incompressible flow of single-phase, Newtonian liquids and gases.

The ESDU validated CFD predictions were used in the update of ESDU 66027²⁶. Full details of the CFD validation studies can be found in ESDU TN 08008⁴⁸ and ESDU TN 08009⁴⁹.

The characteristic parameters of the flow in straight pipes are presented in Section 4. The friction losses and flow characteristics are described in Section 5. The two Benchmarks are presented in Sections 6 and 7.

The CFD methodology used by ESDU to perform the validated CFD predictions is summarized in Section 8.

The ESDU CFD Best Practice Guidelines for the modelling of friction losses and flow characteristics in straight pipes are provided in ESDU CFD-BPG 09010⁵⁰.

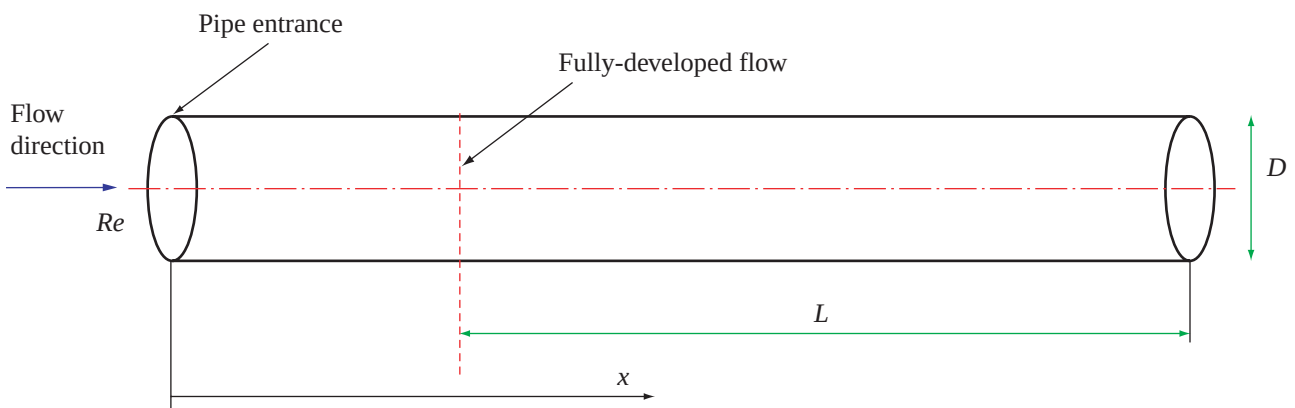
4. CHARACTERISTIC PARAMETERS

The characteristic geometrical and flow parameters used here for straight pipes (see Sketch 4.1) are:

- the pipe length to diameter ratio, L/D ,
- the pipe Reynolds number, Re , defined as

$$Re = \frac{u_{mean} D}{\nu}, \quad (4.1)$$

where u_{mean} is the mean velocity across the pipe cross-section and ν is the fluid kinematic viscosity.



Sketch 4.1 Straight pipe characteristic parameters

In pipe entrance problems, the ratio of the distance from the entrance to the pipe diameter,

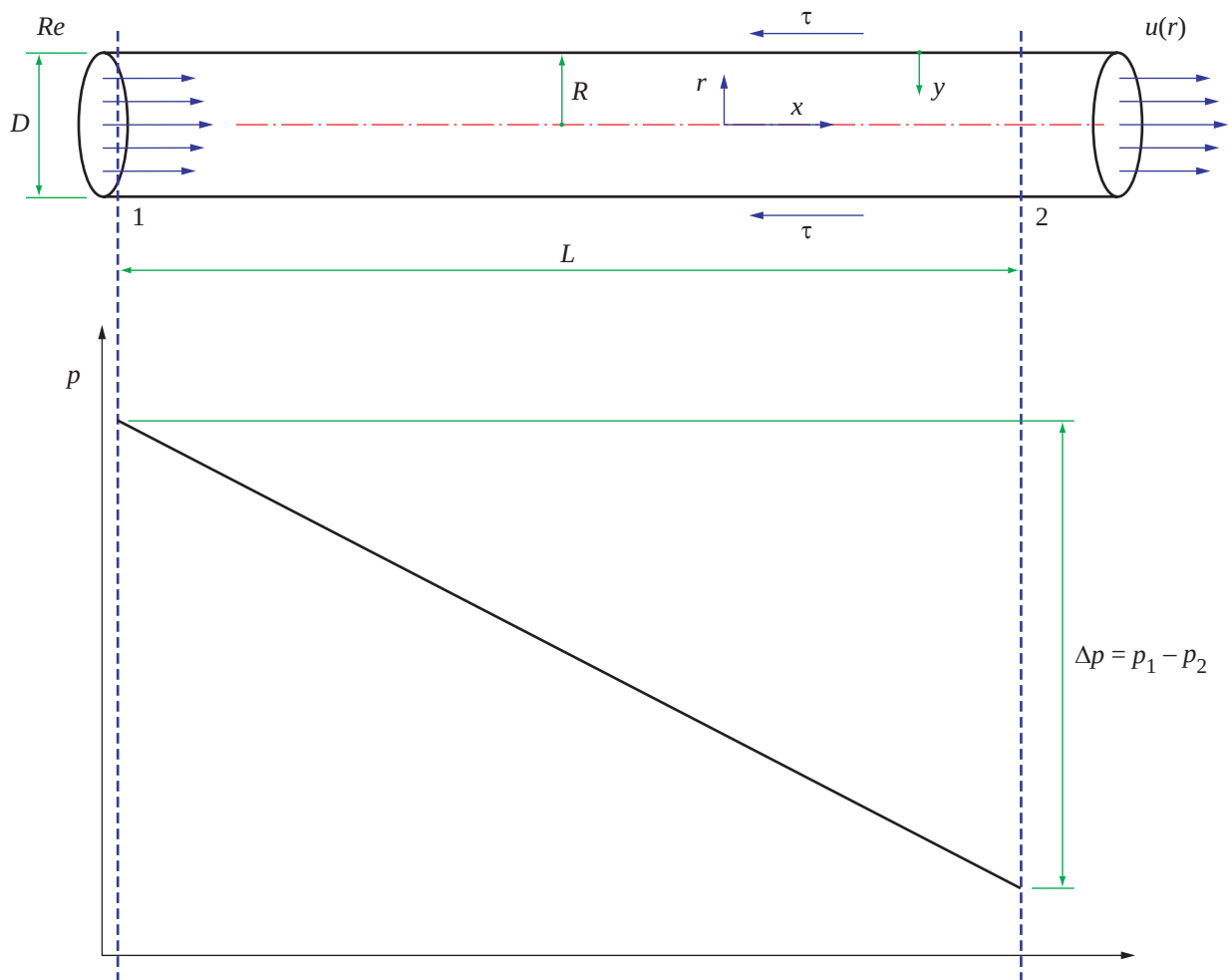
$$x/D,$$

is used as the characteristic geometrical parameter.

5. PIPE FRICTION LOSSES AND FLOW CHARACTERISTICS

A detailed description of the friction losses and flow characteristics in straight pipes with smooth walls is given in ESDU TN 08008⁴⁸ and ESDU TN 08009⁴⁹. The ESDU correlations for friction losses in straight pipes for fully-developed flow conditions are provided in ESDU 66027²⁶.

The main features of the flow in a straight pipe with circular cross-section in fully-developed flow conditions are illustrated in Sketch 5.1. The axial local velocity, $u(r)$, is zero at the pipe wall and maximum at the centreline.



Sketch 5.1 Schematic of flow in a straight pipe

At the pipe entrance, the fluid cross-sectional velocity profile can be considered uniform as is typically assumed for a pipe entrance from a large tank*. As the fluid enters the pipe, the velocity distribution along the pipe length varies with the distance from the inlet due to the influence of friction. Under steady-state conditions, at a certain distance from the entrance, the velocity distribution across the section becomes independent of the axial coordinate and hence reaches a condition known as a 'fully-developed' in which the pressure gradient is constant.

* In practice, this profile can be closely achieved using a 'bell-mouth' entry.

5.1 Friction Losses

In a straight circular pipe, the pressure drop, $\Delta p = p_1 - p_2$, due to friction, can be expressed in terms of the friction factor, f , as

$$\Delta p = 4f \frac{L}{D} \frac{1}{2} \rho u_{mean}^2. \quad (5.1)$$

Different definitions of the friction factor are used in different engineering areas. In civil engineering, for example, a friction factor, λ , defined as

$$\lambda = 4f \quad (5.2)$$

is typically used.

As shown in ESDU TN 08008⁴⁸, both in laminar and turbulent flows, the shear stress at the wall, τ_w , can be determined from the pressure gradient along the pipe:

$$\tau_w = \frac{p_1 - p_2}{L} \frac{R}{2}. \quad (5.3)$$

From Equations (5.1) and (5.3), τ_w can be expressed in terms of the friction factor as

$$\tau_w = \frac{1}{2} f \rho u_{mean}^2. \quad (5.4)$$

As shown in ESDU TN 08008⁴⁸, in **laminar flow**, the friction factor can be derived as

$$f = \frac{16}{Re}. \quad (5.5)$$

In **turbulent flow**, several empirical correlations for the friction factor are available based on a large number of measurements.

A summary of the correlations and measurements available in the literature is given in ESDU TN 08008⁴⁸ and ESDU TN 08009⁴⁹.

5.2 Flow Characteristics

5.2.1 Velocity

The velocity distribution in pipes is often reported in non-dimensional terms* as u^+ in function of y^+ . These are defined as:

$$u^+ = \frac{u}{u_\tau} \quad (5.6)$$

$$y^+ = y u_\tau / \nu, \quad (5.7)$$

* Used in the formulation of pipe "universal law" (see ESDU TN 08008⁴⁸).

where the friction velocity is defined as

$$u_{\tau} = \sqrt{\tau_w / \rho}. \quad (5.8)$$

5.2.2 Development length

The pipe length required to achieve fully-developed flow conditions is referred as to the development length, L_d . This is usually defined as the length required for the centreline velocity, u_{cl} , to achieve 99% of the theoretical or calculated fully-developed flow value.

In laminar and transitional flows, development lengths vary widely depending on the Reynolds number. In turbulent flow, the transition to turbulence at the pipe entrance needs to be taken into account. A summary of the data in the literature for the development length is given in ESDU TN 08008⁴⁸ and ESDU TN 08009⁴⁹.

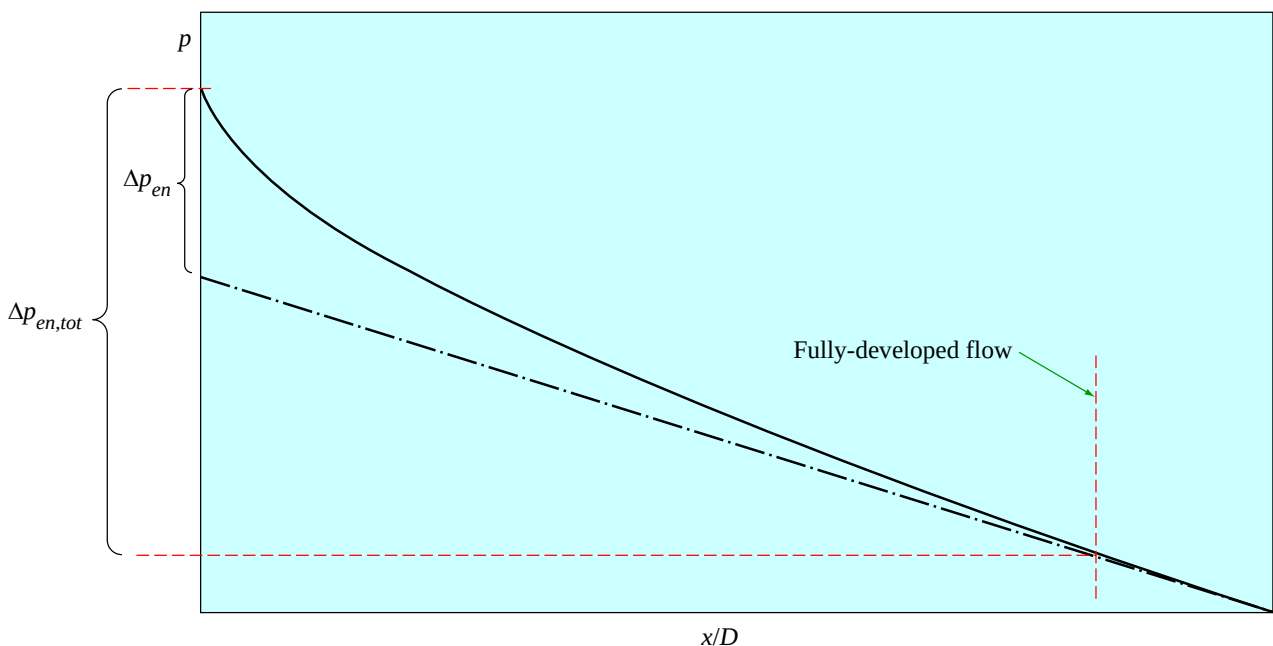
5.2.3 Entrance pressure drop

At a pipe entrance, the pressure gradient is higher than in the fully-developed region (see Sketch 5.2). If the velocity distribution at the pipe entrance is considered approximately uniform, as the fluid enters the pipe, the acceleration of the flow central core and the higher wall shear cause a larger pressure gradient than that in fully developed flow.

This additional entrance pressure drop, Δp_{en} , can be expressed as

$$\Delta p_{en} = K_{en} \frac{\rho u_{mean}^2}{2}, \quad (5.9)$$

where K_{en} is the non-dimensional additional pressure drop (Sketch 5.2).



Sketch 5.2 Definition of entrance pressure drop

A summary of the data in the literature for K_{en} is given in ESDU TN 08008⁴⁸ and ESDU TN 08009⁴⁹.