



CFD Benchmarks for predicting pressure loss and flow characteristics Incompressible flow in sudden contractions

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THE PREPARATION OF THIS CFD GUIDE

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CFD BENCHMARKS FOR PREDICTING PRESSURE LOSS AND FLOW CHARACTERISTICS INCOMPRESSIBLE FLOW IN SUDDEN CONTRACTIONS

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CFD BENCHMARKS FOR PREDICTING PRESSURE LOSS AND FLOW CHARACTERISTICS

INCOMPRESSIBLE FLOW IN SUDDEN CONTRACTIONS

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 circular pipes with sudden contractions in incompressible flow. Input geometrical and flow parameters for sharp-, round-, and chamfer-edged contractions in laminar to turbulent flow are provided for defining four CFD Benchmarks. Comparisons of the benchmark data with ESDU CFD predictions performed using the validation methodology described in ESDU TN 06023³ are discussed in detail.

2. NOTATION AND UNITS

		SI Unit
A_C	Couette coefficient, defined in Equation (7.1)	–
A_H	Hagenbach coefficient, defined in Equation (7.1)	–
A_1	upstream pipe cross-sectional area	m ²
A_2	downstream pipe cross-sectional area	m ²
A_2/A_1	contraction area ratio	–
D_1	upstream pipe diameter	m
D_2	downstream pipe diameter	m
J_{KE}	kinetic-energy profile factor, defined in Equation (5.8)	–
J_M	momentum profile factor, defined in Equation (5.9)	–
K_{si}	static pressure loss coefficient, defined in Equation (5.4)	–
$K_{ti,aw}$	area-weighted mean total pressure loss coefficient, defined in Equation (5.7)	–
$K_{ti,CM}$	continuity-mean total pressure loss coefficient, defined in Equation (5.5)	–
$K_{ti,mw}$	mass-flow-weighted mean total pressure loss coefficient, defined in Equation (5.6)	–
l_e	edge chamfer length	m
L_r	downstream recovery length	m

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		SI Unit
L_{s1x}	upstream separation length	m
L_{s1r}	upstream separation height	m
L_{s2x}	downstream separation length	m
L_{s2r}	downstream separation height	m
L_{u1}	upstream pipe length	m
$L_{x,vc}$	<i>vena contracta</i> axial location	m
L_{2d}	downstream pipe length	m
p	static pressure	Pa
p_u	static pressure at station u	
p_t	total pressure	Pa
r	edge radius	m
R_1	upstream pipe radius	m
R_2	downstream pipe radius	m
Re_1	upstream Reynolds Number	–
Re_2	downstream Reynolds Number	–
u	axial local fluid velocity	m/s
u_{cl}	axial local centre-line velocity	m/s
u_τ	friction velocity, defined as $\sqrt{\tau_w/\rho}$	m/s
v	radial local fluid velocity	m/s
V_1	upstream bulk velocity, $V_1 = m/(\rho A_1)$	m/s
V_2	downstream bulk velocity, $V_2 = m/(\rho A_2)$	m/s
x	axial distance from contraction plane	m
y	radial distance	m
Y_{plus}	non dimensional distance from the wall of first mesh node, defined in Equation (10.1)	–

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		<i>SI Unit</i>
β	diameter contraction ratio, $\beta = D_1/D_2$	–
ϕ	edge chamfer angle	degree
$\lambda_{r,CM}$	continuity-mean round-edge factor, defined in Equation (5.10)	–
$\lambda_{c,CM}$	continuity-mean chamfer-edge factor, defined in Equation (5.11)	–
μ	fluid dynamic viscosity	Pa s
ρ	fluid density	kg/m ³
τ_w	wall shear stress	N/m ²
Δy	distance from wall of first mesh node	m

3. INTRODUCTION

ESDU CFD-BMK 07009 provides CFD Benchmarks recommended by ESDU for the validation of the predictions for pressure loss and flow characteristics in circular pipes with sudden contractions. There are few reliable experimental data on pressure loss in sudden contractions, especially for round-edged and chamfer-edged sudden contractions. The benchmark data presented here are based on reliable measurements and correlations from

- the published literature (Derivations 4 to 32, and 34), and
- Private Communications (Derivations 37, 38, 40),

Four CFD Benchmarks are presented that cover the geometrical configurations and flow Reynolds numbers summarised in Table 3.1.

TABLE 3.1 Summary of the CFD Benchmarks for flow in sudden contractions

Benchmark	A_2/A_1	Re_1	Edge Type	r/D_2	l_e/D_2	ϕ
1	0.285	1 to 10^6	Sharp	–	–	–
2	0.135, 0.332, 0.629	1 to 10^6	Sharp	–	–	–
3	0.135	10^5	Rounded	0.0 – 0.2	–	–
4	0.135, 0.332, 0.629	1.5×10^5	Chamfered	–	0 to 0.2	0° to 90°

The ESDU validated CFD predictions presented here were performed using the following assumptions:

- axisymmetric geometrical configurations with circular cross-section,
- incompressible, single-phase, Newtonian fluid,
- fully-developed flow conditions upstream and downstream of the contraction.

The ESDU validated CFD predictions presented here were used in the development of the correlations for sudden contractions in ESDU 05024². Full details of the CFD validation studies can be found in ESDU TN 06023³.

The characteristic parameters of the flow in sudden contractions are presented in Section 4. The pressure loss and flow characteristics are described in Section 5. The four Benchmarks are presented in Sections 6 to 9. The CFD methodology used by ESDU to perform the validated CFD predictions is summarized in Section 10.

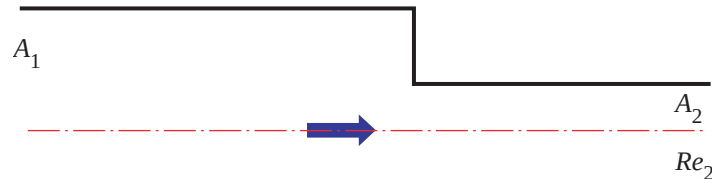
The ESDU CFD Best Practice Guidelines for the modelling pressure loss and flow characteristics in sudden contractions are provided in ESDU CFD-BPG 07008⁴⁵.

4. CHARACTERISTIC PARAMETERS

The characteristic flow parameter used here for sharp-, round-, and chamfer-edged sudden contractions is the Reynolds number downstream of the contraction, Re_2 (Sketches 4.1 to 4.3).

4.1 Sharp-edged Contractions

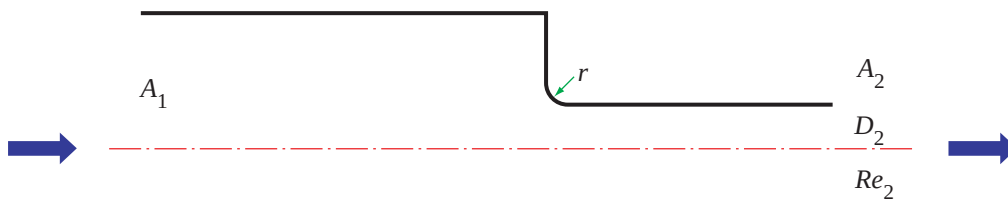
The characteristic geometrical parameter for a sharp-edged sudden contraction, shown in Sketch 4.1, is the contraction area ratio, A_2/A_1 .



Sketch 4.1 Characteristic parameters of a sharp-edged contraction

4.2 Round-edged Contractions

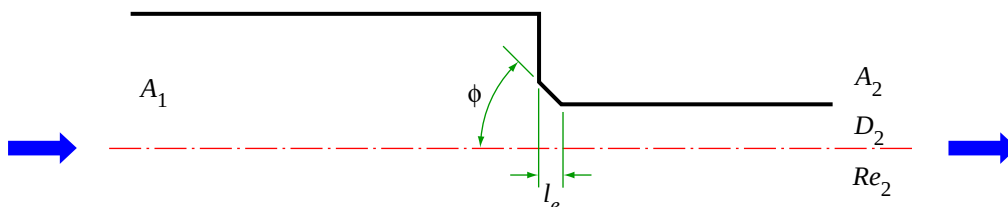
The characteristic geometrical parameters for a round-edged sudden contraction, shown in Sketch 4.2, are the contraction area ratio A_2/A_1 and the radius to diameter ratio r/D_2 .



Sketch 4.2 Characteristic parameters of a round-edged contraction

4.3 Chamfer-edged Contractions

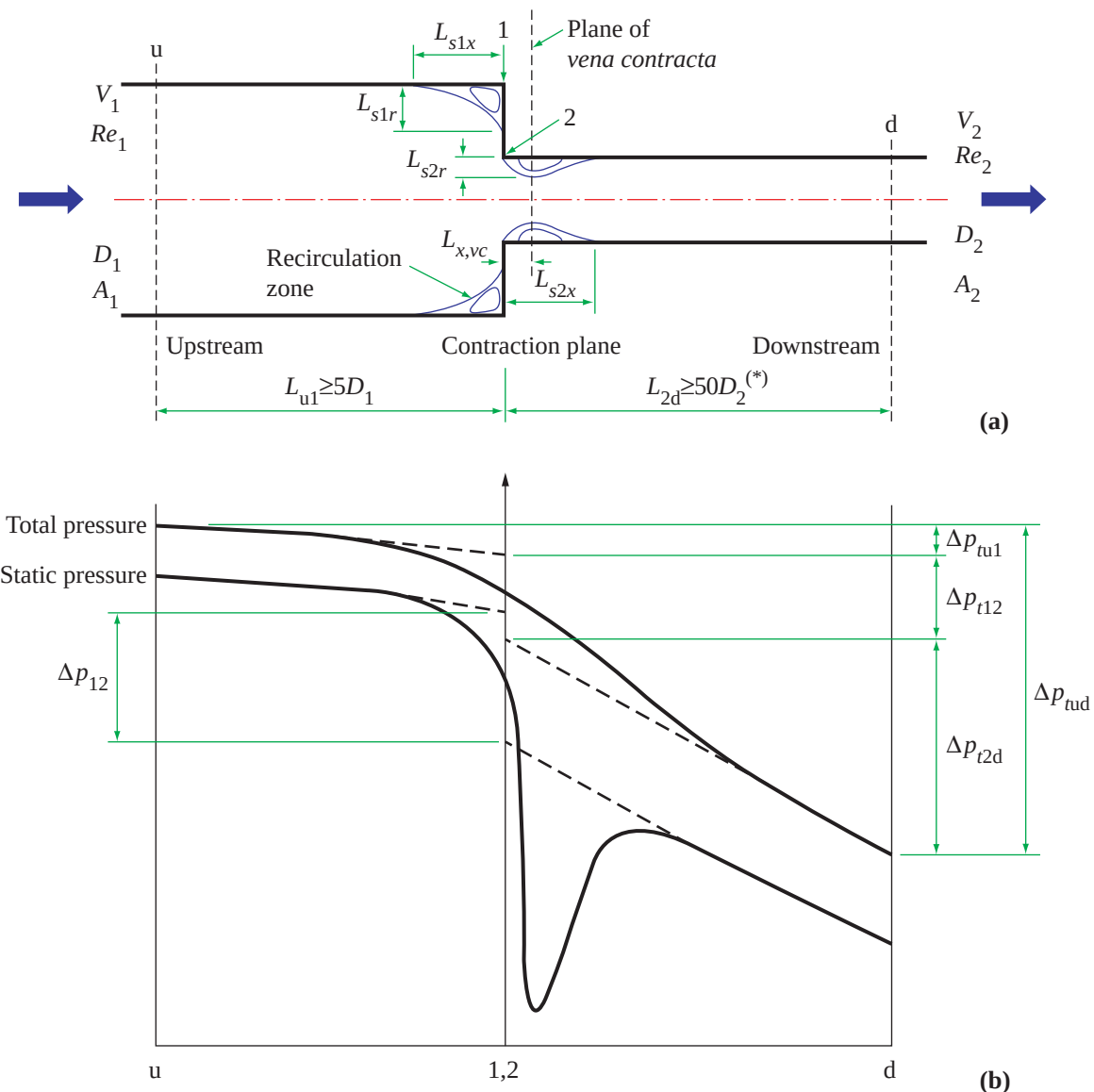
The characteristic geometrical parameters for a chamfer-edged sudden contraction, shown in Sketch 4.3, are the contraction area ratio A_2/A_1 , the chamfer length to diameter ratio, l_e/D_2 , and the chamfer angle, ϕ .



Sketch 4.3 Characteristic parameters of a chamfer-edged contraction

5. PRESSURE LOSS AND FLOW CHARACTERISTICS IN SUDDEN CONTRACTIONS

A detailed description of the pressure loss and flow characteristics in sudden contractions is given in ESDU 05024². The main feature of the flow in sudden contractions is represented by the flow separations in the vicinity of the contraction plane (see Sketch 5.1). These recirculation regions induce a pressure loss across the contraction as a result of two consecutive processes: (1) contraction of the flow to the *vena contracta*, and (2) enlargement of the flow cross-section in an adverse pressure gradient. The smaller the contraction area ratio, A_2/A_1 , the larger is the loss.



Sketch 5.1 (a) Schematic of flow through a sharp-edged sudden contraction.
(b) Centreline static- and total-pressure distributions near plane of contraction

(*) This is valid for turbulent flow. In laminar flow, $L_{2d} \geq 110D_2$ may be required

5.1 Pressure Loss

To calculate the pressure loss in a pipe with a sudden contraction, it is required to determine the total-pressure loss coefficient. This is defined as a function of the downstream bulk-mean velocity,

$$V_2 = \frac{m}{\rho A_2}, \text{ as}$$

$$K_{ti} = \frac{\Delta p_{t12}}{\frac{1}{2}\rho V_2^2} \quad (5.1)$$

where Δp_{t12} (see Sketch 5.1) is the mean-total-pressure loss due to the contraction between station 1, upstream of the contraction, and station 2, downstream of the contraction plane, and is defined as the difference between the total-pressure loss between stations u and d, Δp_{tud} , and the losses due to friction for fully-developed flow conditions in the upstream duct (Δp_{tu1}) and downstream duct (Δp_{t2d}), extrapolated to the contraction plane:

$$\Delta p_{t12} = \Delta p_{tud} - \Delta p_{tu1} - \Delta p_{t2d} \quad (5.2)$$

Total pressures at the upstream and downstream stations u and d are derived from wall static pressures. These must be measured, or obtained from CFD calculations, in regions of fully-developed flow outside the region of influence of the contraction. An exhaustive discussion on the correct location of pressure measurements can be found in Section 3.1 of ESDU 05024². To ensure fully-developed flow upstream of the contraction plane, a duct length of $5D_1$ is usually acceptable. Downstream of the contraction plane, the recovery length, L_r , required to ensure a return to fully-developed flow varies with Reynolds number. In laminar flow, L_r may be as large $110D_2$, in turbulent flow, $L_r \leq 50D_2$.

The total-pressure loss coefficient can be derived from the static-pressure loss coefficient, K_{si} , as

$$K_{ti} = K_{si} - J_d + J_u(A_2/A_1)^2 \quad (5.3)$$

where J_d and J_u are the profile factors that take into account the effect of non-uniform velocity profiles on total pressures across sections u and d (Section 5.1.1). The static-pressure loss coefficient K_{si} is defined as

$$K_{si} = \frac{\Delta p_{12}}{\frac{1}{2}\rho V_2^2} \quad (5.4)$$

5.1.1 Total pressure loss coefficients

Depending on the type of average applied to the velocity profile, different mean-total pressure loss coefficients can be defined⁴³. In most engineering applications, the following mean total pressure coefficients are used:

- the continuity-mean total-pressure loss coefficient:

$$K_{ti,CM} = K_{si} - (1 - (A_2/A_1)^2) \quad (5.5)$$

- the mass-flow-weighted mean total-pressure loss coefficient:

$$K_{ti,mw} = K_{si} - J_{KE,d} + J_{KE,u}(A_2/A_1)^2 \quad (5.6)$$

- the area-weighted mean total-pressure loss coefficient:

$$K_{ti,aw} = K_{si} - J_{M,d} + J_{M,u}(A_2/A_1)^2 \quad (5.7)$$

where $J_{KE,d}$ and $J_{KE,u}$ are the kinetic-energy profile factors at stations d and u, respectively, and $J_{M,d}$ and $J_{M,u}$ are the momentum profile factors at stations d and u, respectively. These are defined by:

$$J_{KE} = \frac{1}{m} \int_m \left(\frac{u}{V} \right)^2 dm = \frac{1}{A} \int_A \left(\frac{u}{V} \right)^3 dA \quad (5.8)$$

$$J_M = \frac{1}{A} \int_A \left(\frac{u}{V} \right)^2 dA \quad (5.9)$$

Total and static pressure loss coefficients are a function of the Reynolds number and the contraction characteristic geometrical parameters. Correlations for such coefficients, based on reliable experimental data and the ESDU CFD studies presented in ESDU TN 06023³, are in ESDU 05024².

5.1.2 Round-edged contractions

Edge rounding (Sketch 4.2) is used to reduce the pressure drop across the contraction. This effect can be quantified using the continuity-mean round-edge factor:

$$\lambda_{r,CM} = \frac{K_{ti,CM}}{K'_{ti,CM}} \quad (5.10)$$

where $K_{ti,CM}$ is the continuity-mean total-pressure loss coefficient for the round-edged sudden contraction, and $K'_{ti,CM}$ is the continuity-mean total-pressure loss coefficient for the sharp-edged sudden contraction with the same contraction area ratio.

5.1.3 Chamfer-edged contractions

Edge chamfering (Sketch 4.3) also reduces the pressure loss across a contraction. The effect on pressure loss of edge chamfering can be quantified using the continuity-mean chamfer-edge factor:

$$\lambda_{c,CM} = \frac{K_{ti,CM}}{K'_{ti,CM}} \quad (5.11)$$

where is $K_{ti,CM}$ the total pressure coefficient for the chamfer-edged sudden contraction, and $K'_{ti,CM}$ is the total-pressure loss coefficient for the sharp-edged sudden contraction with the same contraction area ratio.

5.2 Flow Patterns

Detailed information on the flow characteristics in sharp-, round-, and chamfer-edged sudden contractions is provided in Section 4.3.1 of ESDU 05024².

5.2.1 Sharp-edged contractions

In a sharp-edged sudden contraction, the extent of the upstream and downstream flow separations varies with contraction area ratio, A_2/A_1 , and Re . For a given contraction area ratio, A_2/A_1 , a flow separation occurs upstream of the contraction even at low Re . A downstream flow separation and reattachment develops at a particular Reynolds number depending on A_2/A_1 . In laminar flow with low Reynolds number, the upstream separation size (length and height), decreases slightly with increase in Re , until it reaches a minimum value. Then it increases with Re until the fully turbulent flow regime is reached. In turbulent flow it reduces slightly with Re . The size of the downstream separation increases with Re in laminar and transitional flow. In turbulent flow, it reduces slightly with Re .

5.2.2 Round- and chamfer-edged contractions

Separation sizes in round-edged sudden contractions are generally smaller than for sharp-edged contractions.

In chamfer-edged sudden contractions, the flow separation size and location are a complex function of the chamfer geometry (chamfer length ratio and angle) and flow Re . The flow may separate:

- at only the upstream corner of the chamfer,
- at only the downstream corner of the chamfer,
- at both the upstream and the downstream corners of the chamfer,
- or it may never separate.

The separated flow may then reattach:

- downstream of the chamfer,
- on the chamfer with further downstream separation,
- on the chamfer with no further downstream separation.

Detailed information on the flow separation characteristics in chamfer-edged sudden contractions can be found in Appendix D of ESDU 05024².

6. BENCHMARK 1: SHARP-EDGED SUDDEN CONTRACTION WITH $A_2/A_1 = 0.285$ AND $1 \leq Re_1 \leq 10^6$

The geometrical parameters for this Benchmark are based on the work by Durst and co-workers^{24,31}:

$$A_2/A_1 = 0.285 \text{ and } D_1 = 19.1 \text{ mm.}$$

The flow conditions were extended to transitional and turbulent flow:

$$1 \leq Re_1 \leq 10^6.$$

6.1 Validation Data

A summary of the experimental and numerical data used for this Benchmark is given in Table 6.1.

Validation data for the axial and radial velocities, pressure distribution and separation size in laminar flow were based on Durst's data^{24,31}. Validation data for the pressure loss coefficient were from Kaye and Rosen²¹, Kays⁸, Bullen *et al.*³⁴ experimental data, and Kays⁸, ESDU 01016⁹, and Curzons⁴¹ correlations. A description of the experimental techniques used in the validation data is presented in Section 6.1.1.

TABLE 6.1 Summary of the validation data for Benchmark 1

Reference	Technique	Data	Data Format	Re_1
Durst and Loy ²⁴ Buckle and Durst ³¹	Experimental	Axial and radial velocities	Tables and graphs	23, 196, 372, 968, 1213
	Experimental	Separation size	Graphs	23 to 1213
Kaye and Rosen ²¹	Experimental	Pressure loss coefficient	Correlation	4 to 1100
Kays ⁸	Experimental and semi-empirical ($A_2/A_1 = 0.280$)	Pressure loss coefficient	Graphs and correlation	550 to 20 000
Bullen <i>et al.</i> ³⁴	Experimental ($A_2/A_1 = 0.297$)	Pressure loss coefficient	Graphs	$4 \cdot 10^4$ to $2 \cdot 10^5$
ESDU ¹	Correlation	Pressure loss coefficient	Correlation	$\geq 10^4$
Curzons ⁴¹	Semi-empirical	Pressure loss coefficient	Correlation	10 to 10^6

6.1.1 Experimental techniques

6.1.1.1 LDA measurements ($23 \leq Re_1 \leq 1213$)

In the LDA measurements of Durst and co-workers^{24,31}, the test section consisted of a glass pipe with sudden change in cross section, mounted inside a channel filled with same fluid. The fluid was oil-Palatinol mixture with the same refractive index as the glass of the pipe wall, kept under controlled temperature conditions. A three-dimensional traversing system was used to allow precise positioning of the measuring point at any location inside the pipe. The Laser Doppler system consisted of a 15 mW-Helium-Neon-Laser and a compact optical system, incorporating a double Bragg cell device for frequency shifting the laser beams. The effective measuring control volume was 200 μm in diameter and about 1600 μm in length. Measurements were carried at various sections upstream and downstream of the contraction plane.

The reported estimated global uncertainty of the measurements was within 2% with 95% confidence. This was derived from the following reported uncertainties:

- Signal processing electronics of LDA-system: 1%
- Traversing unit: 1%
- Mass flow rate oscillations: 0.5%

6.1.1.2 Separation size measurements ($23 \leq Re_1 \leq 1213$)

Durst and co-workers^{24,31} carried out observations of the separation regions by the illumination of a laser light sheet. Measurements of the separation bubble developing downstream of the contraction plane were provided as length and height of the separation. Details of the flow inside the separation could not be obtained, as a control volume of 20 μm is required. Based on the information provided and the scatter of the experimental data, the uncertainty of the measurements can be estimated as $\pm 30\%$. The upstream separation region could not be resolved and only visual observations were carried out to analyse the variation of the recirculation size with Re .

6.1.1.3 Pressure loss coefficient ($4 \leq Re_1 < 2 \times 10^5$)

The experimentally based correlations of Kaye and Rosen²¹ and Sylvester and Rosen²⁰ for the static pressure loss coefficient K_{Si} are for $A_2/A_1 = 0.041$ to 0.636 and $Re_1 = 4$ to 1100 . The experimental uncertainty was not reported by Kaye and Rosen, but could be estimated from the minimum precision reported: ± 0.02 inHg. Different glycerine-water solutions were used for different Reynolds number but only the minimum and maximum values of 30% to 95% solutions of glycerine in water were specified. It can be assumed that the solution with the highest glycerol content was used for lowest Reynolds number ($Re_2 = 6$) and that with the smallest glycerol content was used at the highest Reynolds number ($Re_2 = 2004$). If it is then assumed that the experimental error was only due to measurements at the inlet of the contraction, the resulting estimated uncertainty is about $\pm 80\%$ at $Re_2 = 6$ and $\pm 20\%$ at $Re_2 = 2004$.

Measurement uncertainties for Kays' data⁸ are not reported. Measurement uncertainties for Bullen's data³⁴ are discussed in Section 7.1.1.

6.2 Comparisons with ESDU CFD Calculations

Comparisons of the ESDU CFD results with the validation data described in Table 6.1 are shown in Figures 1 to 8 and discussed in the following Subsections. The CFD methodology used in the ESDU CFD calculations is described in Section 10.

6.2.1 Velocity profiles

The ESDU CFD predictions for the axial and radial velocities were compared with the LDA data of Durst and co-workers^{24,31} at different axial locations, upstream and downstream of the contraction, and at different Reynolds numbers: $23 \leq Re_1 \leq 1213$. In general, the CFD results predicted well the main observed and measured flow features, qualitatively and quantitatively. Both ESDU CFD predictions and LDA measurements showed that upstream of the contraction plane and at a distance equal to 1 to $2D_1$, the axial velocity profiles start to deform with higher values in the central volume of the pipe. In the vicinity of the contraction plane, the flow decelerates near the wall and accelerates in the central region. For $Re_1 \geq 125$, the velocity profile downstream of the contraction displays a typical overshoot with a peak close to the wall and a flat region in the pipe central section. For $Re_1 \geq 300$, a downstream separation occurs with reverse flow and negative axial velocities in the vicinity of the wall.

Comparisons of the ESDU CFD predictions with the LDA measurements for $Re_1 < 300$ (no downstream separation) showed that the axial velocity is predicted well, qualitatively and quantitatively. For $Re_1 > 300$, the CFD results showed slightly lower peaks in the velocity overshoot region. Comparisons with radial velocities showed a good qualitative agreement, but some discrepancies are evident which may be due to the small values measured by Durst and co-workers^{24,31}. Typical comparisons for the axial velocities at $Re_1 = 23, 196$ and 1213 are shown in Figures 1, 2, and 4, respectively. Typical comparisons for the radial velocities at $Re_1 = 196$ are shown in Figure 3.

At low Reynolds number, $Re_1 = 23$, some significant discrepancies of the axial velocity are present upstream (Figure 1(A)) and downstream (Figure 1(B)) of the contraction plane. For $Re_1 = 196$, discrepancies are lower. The upstream axial velocities are predicted well (Figure 2(A)). The downstream axial velocities are slightly over-predicted at the pipe axis and at the velocity overshoot peak (Figure 2(B)). The CFD radial velocities for the same Reynolds number (Figure 3) predict well the trends of the LDA measurements, but under-predict the equivalent LDA measurements.

Comparisons of the axial velocities for $Re_1 = 1213$ are shown in Figure 4. The upstream velocities are predicted quite well (Figure 4(A)). The downstream velocities (Figure 4(B)) at the axis are slightly over-predicted in the vicinity of the contraction plane. The peak overshoot is slightly under-predicted. In the recirculation region, no LDA data are available for comparison.

More details on these comparisons can be found in ESDU TN 06023³.

6.2.2 Separation size

Both Durst observations^{24,31} and ESDU CFD predictions showed that a separation occurs upstream of the contraction even at low Re . With the increase in Re , the upstream separation size (length and height) decreases slightly to reach a minimum value at about $Re_1 = 100$. At $Re_1 > 300$ – 400 , a separation region develops immediately downstream of the contraction. The size of this separation increases with Re in the laminar and transitional flow regimes.

In laminar flow, the ESDU CFD predictions of the upstream separation length and height show a decrease in size for $Re_1 < 100$ and then a linear increase. These predictions are in good agreement with Durst observations^{24,31}.

The ESDU CFD predictions of the upstream separation length and height in transitional and turbulent flow are also shown in Figure 5. Predictions using the $\kappa - \varepsilon$ model with the SCALEABLE near-wall treatment are significantly lower than those using the $\kappa - \omega$ or the SST models with the AUTOMATIC near-wall treatment. Predictions using the $\kappa - \omega$ or the SST models are similar and very close for $Re_1 > 10^5$. They are consistent with the laminar flow predictions.

Downstream of the contraction plane, the ESDU CFD calculations predict the occurrence of flow separation for $Re_1 > 300$. In laminar flow, the size of this separation increases with Re_1 . This is consistent with the experimental observations by Durst^{24,31}. Comparisons of the downstream separation size in Figure 6 show that ESDU CFD predictions are within the experimental uncertainty of $\pm 30\%$.

In turbulent flow, the ESDU CFD predictions using SST and $\kappa-\omega$ models with the AUTOMATIC near-wall treatment display similar trends. Predictions using the $\kappa-\epsilon$ model with the SCALEABLE near-wall treatment are significantly lower.

6.2.3 Pressure loss coefficient

6.2.3.1 Static pressure loss coefficient

Comparisons of the experimental correlation of Kaye and Rosen²¹ with ESDU CFD predictions for the static pressure loss coefficient, K_{si} , are shown in Figure 7. These data are for laminar flow. It is assumed that the estimated experimental uncertainty for $Re_2 = 1$ and 2271 is $\pm 80\%$ and 20%, respectively (see Section 6.1.1). The ESDU CFD predictions are lower than the experimental data for the whole laminar flow range. However, they are within the estimated experimental uncertainty.

6.2.3.2 Total pressure loss coefficient

Comparisons of the experimental data of Kaye and Rosen²¹, Kays⁸ and Bullen *et al.*³⁴, and the correlations of Kays⁸, ESDU¹ and Curzons⁴¹ with ESDU CFD predictions for the continuity-mean total pressure loss coefficient, $K_{ti,CM}$, are shown in Figures 8(A) and (B). These data are for laminar, transitional and turbulent flows. Experimental data by Kays⁸ and Bullen *et al.*³⁴ are for contraction ratios $A_2/A_1 = 0.280$ and 0.297, respectively. The estimated experimental uncertainty for Bullen's measurements was $\pm 15\%$ for $Re_2 = 4 \times 10^4$ and $\pm 6\%$ for $Re_2 = 4 \times 10^5$.

In laminar flow, the ESDU CFD predictions are lower than Kaye and Rosen data²¹. However, they are higher than Kays data⁸ for $550 < Re_2 < 2000$. Kays measurements are in good agreement with his correlation for $1000 < Re_2 < 4000$. Curzons correlation⁴¹ is significantly lower than ESDU CFD predictions.

In transitional flow, the ESDU CFD predictions were obtained using the $\kappa-\omega$ turbulence model with the AUTOMATIC near-wall treatment. These results are compared with Curzons correlation⁴¹ and Kays⁸ measurements and correlation data in Figure 8(A) and (B). For $3000 < Re_2 < 4000$, Kays' experimental data are close to his correlation but lower than ESDU CFD predictions. For $6000 < Re_2 < 7000$, Kays' experimental data are very close to ESDU CFD predictions, but higher than his correlation. Curzons correlation is in agreement with ESDU CFD predictions and Kays experimental data.

In turbulent flow, the ESDU CFD predictions are compared with the experimental data of Bullen *et al.*³⁴ and the correlations of Kays⁸, ESDU¹ and Curzons⁴¹ in Figures 8(A) and (B). The ESDU CFD predictions shown in Figure 8(A) were calculated using $\kappa-\omega$ turbulence model with the AUTOMATIC near-wall treatment. The ESDU CFD predictions using the $\kappa-\epsilon$ model with the SCALEABLE wall function are also shown in Figure 8(B). The ESDU CFD predictions using the SST model with the AUTOMATIC near-wall treatment are lower than those using the $\kappa-\epsilon$ model and are not shown in these Figures. The ESDU correlation¹ is significantly higher than Bullen's measurements, Kays and Curzons's correlations, and ESDU CFD predictions, both using $\kappa-\omega$ and $\kappa-\epsilon$ models.

7. BENCHMARK 2: SHARP-EDGED SUDDEN CONTRACTIONS WITH $A_2/A_1 = 0.135, 0.332, 0.629$ AND $1 \leq Re_1 \leq 10^6$

The geometrical parameters for this Benchmark are based on the work by Bullen and co-workers^{26-29,34}:

$$A_2/A_1 = 0.135, 0.332, 0.629 \text{ and } D_1 = 110.17 \text{ mm}.$$

The flow conditions were extended to laminar and transitional flow:

$$1 \leq Re_1 \leq 10^6.$$

7.1 Validation Data

A summary of the data used for this Benchmark is given in Table 7.1. Validation data for the axial and radial velocities, and separation core extent in turbulent flow were based on Bullen's data for $A_2/A_1 = 0.332$. Validation data for the pressure loss coefficient are from Harris⁵, Benedict *et al.*¹⁶, Kaye and Rosen²¹ and Bullen *et al.*³⁴ experimental data, and Kays⁸, Crane¹⁴, Miller³⁰, Idel'chik³², ESDU¹, and Curzons⁴¹ correlations. A description of the experimental techniques used in the validation data is presented in Section 7.1.1.

The validation data for the Couette coefficient, A_C , and Hagenbach coefficient, A_H , defined by Holmes¹⁷ for the static pressure loss coefficient in laminar flow as

$$K_{si} = A_H + A_C/Re_2, \quad (7.1)$$

are from the sources described in Tables 7.2 and 7.3, respectively. The Couette coefficient is the controlling factor for pressure losses at very low Reynolds numbers, flow conditions. The Hagenbach coefficient is the controlling factor for pressure losses at higher, sub-transition Reynolds numbers.

The validation data for the downstream recovery length to fully-developed flow, L_r , are from the sources described in Table 7.4.