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A passive loss reduction method of square sudden expansions

Thesis booklet of
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1 Motivation

Due to the rapidly growing population and humankind's increasing need for comfort, energy consumption assumes considerable proportions that continue to rise at an unprecedented rate. A major contributor to this global energy consumption is the building sector, accounting for approximately 30% – 40% of the world's total energy use [1]. Due to the increasing energetic awareness of the engineering society, directives and regulations have been established since the 1970s, prompted by the first oil crisis [2], targeting a general reduction in the energy use of buildings. However, despite the introduction of increasingly stringent legislations, energy consumption in the building sector continues to rise [1, 2], which can be attributed to factors such as population growth and increasing comfort demands.

Mechanical ventilation systems are now indispensable in airtight modern buildings, contributing significantly to overall energy consumption [3]. Consequently, rational energy management in buildings requires a focus on energy-efficient operation of heating, ventilation, and air conditioning (**HVAC**) systems. An important aim is to consider and control the fluid mechanical losses occurring in the components of HVAC systems, among others, in air ducts. This research addresses these losses through two main approaches: precise loss calculations to accurately predict system performance and the reduction of ductwork resistance by addressing losses in individual components.

The field of mechanical ventilation is particularly interesting because ventilation ductwork is often of rectangular cross-section. While circular elements have well-defined dimensions specified by the standards [4], rectangular elements are often tailor-made, making it challenging for manufacturers to provide standardized loss data due to the wide range of possible geometries. Thus, it is important to improve general empirical formulae for accurately calculating losses in rectangular air duct elements. While various components impact air duct resistance, our study concentrates on expansion elements.

Expansion elements are typically incorporated into HVAC systems for two main purposes: to reduce air duct velocity, thereby mitigating associated losses and flow-induced noise, or to recover static pressure. While the most energy-efficient method of increasing the flow cross-section involves using a diffuser with an opening angle of ~6–12° [5], shorter and wider-angled diffusers (ranging from 13° to 67°) are also available on the market. Industry standards [4, 6] set the maximum opening angle at 60°. Notably, diffusers with an opening angle between 40° – 60° exhibit worse energetic characteristics compared to a simple sudden expansion [5], i.e., a 180° diffuser. This fact, together with the frequent limitation of space allowance hindering the use of energetically more favorable but longer diffusers, ratifies the use of sudden expansions in HVAC ducts. Loss reduction of sudden expansions by simple and cost-effective flow-controlling elements gives the potential for a further competitive advantage of the sudden expansions over diffusers.

Based on the above-written, the primary motivation of this dissertation is to address and reduce the losses induced by sudden expansions installed in rectangular air duct systems. Despite the seemingly simple nature of this topic and its prevalence in existing scholarly work, there are still gaps in the available knowledge, leaving room for further exploration.

2 Research goals and methods

Flow features – goal #1

The main flow features developing in an axisymmetric sudden expansion are illustrated qualitatively in Fig. 1. A fully developed turbulent flow is approaching the sudden expansion. As it reaches the step edge, the separation of the boundary layer takes place. The detached boundary layer turns into a shear layer, demarcating the border between the main flow and the recirculation zone. Within the recirculation zone, two distinct regions emerge: a higher-velocity primary and a lower-velocity secondary separation zone. The primary separation ends where the flow impinges on the wall, i.e., reattachment takes place, while the secondary separation zone is confined to the step base. Further downstream, a new boundary layer develops in the relaxation region; the flow gradually tends towards a fully developed state.

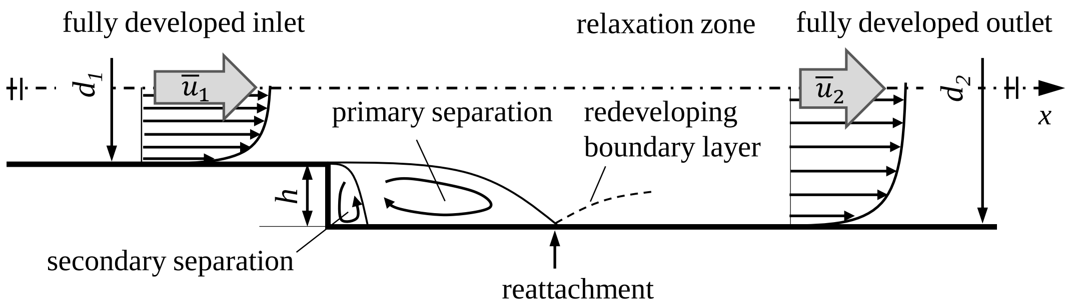

Fig. 1 Basic flow features in axisymmetric sudden expansions.

For facilitating further discussion, two key terms – the Reynolds number (Re_1), describing the flow regime, and the area ratio (n_{AR}), related to the geometry of the sudden expansion – are defined by Eqs. (1) and (2):

$$Re_1 = \frac{\overline{u}_1 \cdot d_1}{\nu} \tag{1}$$

$$n_{AR} = \frac{A_2}{A_1} \tag{2}$$

, where $\overline{u}_1$ is the area-averaged streamwise velocity upstream of the sudden expansions, d_1 is the inner diameter of the upstream pipe section (or hydraulic diameter in the context of square cross-sections), ν is the kinematic viscosity of the fluid, and A_1 and A_2 are the upstream and downstream inner pipe cross-sections, respectively.

In practical terms, both the primary and secondary separation zones hold significance within ventilation systems. The reattachment length serves as a critical parameter, representing the minimum distance below which the installation of flow rate-controlling dampers or flow-measuring devices is discouraged to prevent backflow through these elements. On the other hand, the secondary separation zone, characterized as a low-speed corner vortex, tends to entrain particulate matter, including contaminants, potentially resulting in dust accumulation and pathogen buildup at the step corner. Consequently, it is advisable to incorporate cleaning hatches within the boundaries of the secondary separation zone, underscoring the importance of understanding its extent.

Existing references on axisymmetric sudden expansions [7, 8] suggest that the reattachment length, denoting the extent of the primary separation region, typically falls within the range of 5 – 11*h* (*h* = step height*)*. The secondary separation zone, though rarely discussed in the available literature sources [9], is expected to have an extent falling between 1 – 2*h*. A noteworthy gap in the current scientific literature pertains to the lack of systematic studies investigating the dimensions of the primary and secondary separation zones in the context of square sudden expansions, which highlights the need for further research and sets the first research goal.

Research goal #1: systematic examination of the extent of the primary and secondary separation zones in square sudden expansions as a function of the Reynolds number and the area ratio.

Total pressure loss – goal #2

In hydraulic systems, pipe fittings introduce losses attributed to vortex formation, velocity equalization within the duct, and friction losses caused by the duct wall in the affected region. The loss coefficient (ζ) for any hydraulic component is defined as the dimensionless total pressure loss (Δp_{tot}) across the element (Eq. (3)), with the convention of using the area-averaged upstream dynamic pressure ($\overline{p}_{dyn,1}$) as the nondimensionalizing term.

$$\zeta = \frac{\Delta p_{tot}}{\overline{p}_{dyn,1}} \tag{3}$$

The sudden expansion is exceptional amongst pipe fittings in the sense that there exists a widely known semi-empirical formula for determining its loss coefficient (ζ_{BC}), given in Eq. (4).

$$\zeta_{BC} = \left(1 - \frac{1}{n_{AR}}\right)^2 \tag{4}$$

The formula is widespread both in fluid dynamic textbooks [10, 11] and building service engineering handbooks [12, 13], and it suggests that the loss coefficient of a sudden expansion depends exclusively on the area ratio of the element. While Eq. (4) is undeniably practical due to its simplicity, it is essential to remember that various simplifications were applied during its development, potentially influencing the loss coefficient within specific parameter ranges. One example is to consider the practically non-existent case of a uniform upstream flow instead of a fully developed profile. The impact of these simplifications, as well as a comprehensive discussion of the loss coefficient in the context of square sudden expansions, have been observed to be mostly absent in the scientific literature, which motivates the second research goal:

Research goal #2: systematic examination of the loss coefficient of square sudden expansions, as a function of the Reynolds number and the area ratio, for the case of a fully developed turbulent upstream flow; establishment of a semi-empirical method that describes the loss coefficient of square sudden expansion more accurately than the formula provided in Eq. (4), and assessment of the validity range and uncertainty associated with the provided semi-empirical method.

Static pressure rise – goal #3

Due to the expansion of the area in diffuser flows, the flow velocity reduces, resulting in an increase in the static pressure. A sudden expansion, essentially a diffuser with a 180-degree opening angle, is commonly assessed based on its capacity to convert dynamic pressure into static pressure [5, 11, 13]. This evaluation is typically quantified using the static pressure recovery coefficient (c_{SPR}), defined by Eq. (5) as the static pressure rise (Δp_{SPR}) provided by the element, nondimensionalized by the area-averaged upstream dynamic pressure ($\overline{p}_{dyn,1}$).

$$c_{SPR} = \frac{\Delta p_{SPR}}{\overline{p}_{dyn,1}} \tag{5}$$

Similar to the loss coefficient, there exists a widely-used simplified formula for the description of the static pressure rise of a sudden expansion, as given in Eq. (6):

$$c_{SPR,BC} = \frac{1}{n_{AR}}\left(1 - \frac{1}{n_{AR}}\right) \tag{6}$$

It is noteworthy to explore the static pressure elevation capabilities of expansion elements for the two extrema of zero and infinite are ratios. In the case where n_{AR} = 0, there is no expansion in the cross-section, resulting in an absence of static pressure elevation. Similarly, in the case of $n_{AR} \rightarrow \infty$ – such as when a pipe opens into a large room – again, there is no static pressure increase, as the free jet exiting the pipe maintains static pressure equivalence with the surrounding room pressure. Consequently, the static pressure rise must reach a maximum value within the range of zero and infinite area ratios. This maximum is easily explored analytically by partial differentiation of Eq. (6); however – surprisingly –, it seems to be lacking from the literature.

While the discussion of the static pressure recovery coefficient for axisymmetric sudden expansions is – scarcely though, but – available in the literature, its analysis for the case of square sudden expansions has been observed to be absent. Thus, research goal no. 3 is formulated as follows:

Research goal #3: systematic examination of the static pressure recovery coefficients of square sudden expansions, as a function of the Reynolds number and the area ratio, for the case of a fully developed upstream flow; establishment of a semi-empirical method that describes the static pressure recovery coefficient of square sudden expansion more accurately than the formula provided in Eq. (6), and assessment of the validity range and the uncertainty of the provided semi-empirical method, with particular scrutiny on optimum area ratio to reach the maximum static pressure recovery.

Reduction of losses – goal #4

Modifications of suddenly expanding geometries appear in the literature with generally two main goals: reducing the reattachment length [14] or improving the energetic characteristics [15-17] – i.e., reducing the losses or increasing the static pressure recovery – of the expansion, depending on the final utilization of the modified geometry. The applied changes generally involve the installation of guide vanes inside the element [16] or slight changes in the contour of the sudden expansion [15, 17]. These minor modifications without necessitating any external energy sources are generally termed passive flow control methods.

Based on the relevant scholarly work, flow-controlling methods do appear for axisymmetric sudden expansions; however, modifications of square sudden expansions seem to be lacking in the scientific literature. Consequently, there exists a need to develop a passive flow control method for square sudden expansions that is simple, easy to install, cost-effective, and robust, making it suitable for application in ventilation ducts. The suggested method in the present dissertation is depicted in Fig. 2.

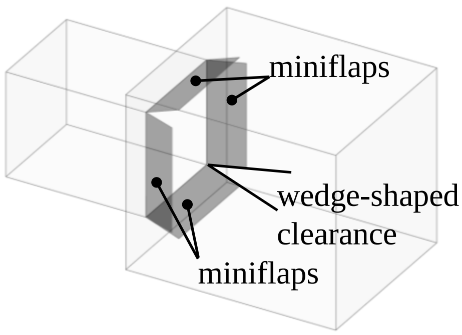

Fig. 2. Passive flow control of square sudden expansions: the miniflap method.

Short, rectangular sheets of adjustable angle – referred to as *miniflaps* from now on – are placed at the step edge of the sudden expansion, acting as a continuation of the upstream duct wall. The miniflaps can be thought of as a short diffuser located at the expansion plane. When the angle of the miniflaps is increased, a wedge-shaped corner clearance appears between the sheets. Considering the practical implementation of the miniflaps, they are presumed to be executed by means of the sheet metal processing technology applied to the realization of the ducts themselves. The flaps are considered appendages of the duct of smaller cross-section, realized by outbending the trailing edges of the duct, providing an easy-to-manufacture and economical configuration. In accordance with the main goals of the flow control methods in suddenly expanding geometries, research goal no. 4 is given as follows:

Research goal #4: systematic investigation of the effect of miniflaps on the losses in flows that develop in square sudden expansions, as a function of the Reynolds number, the area ratio of the sudden expansion, the miniflap length, and the miniflap angle, for the case of a fully developed upstream flow; development of a semi-empirical model to describe the loss coefficient dependency on the aforementioned parameters, and assessment of the model uncertainty.

Methodology

The applied research methodology involved experimental, numerical, and theoretical approaches. First, measurements were conducted in an open-circuit, suction-type wind tunnel, covering a limited range of the entire, practically relevant parameter space. Flow details were mapped using a laser Doppler anemometer (LDA), while losses were determined based on wall static pressure measurements. The experimental data were used to validate the numerical method, which proved to be an economical way to expand the examined parameter range. Numerical simulations were performed using the Ansys Workbench 2021R2 commercial software package. Due to the high number of configurations to be examined, two Reynolds-averaged Navier-Stokes turbulence models were employed: the generalized k-ω (GEKO) and the Stress-BSL version of the Reynolds stress model. Semi-empirical models were developed to determine the loss and static pressure recovery coefficients of square sudden expansions, both with and without miniflaps. The results of the numerical simulations were used to validate the developed semi-empirical models and asses their accuracy.

The next chapter summarizes the new scientific results related to the four research goals presented above in the form of scientific theses referred to as *contributions*.

3 Contributions

The literature lacks data on flow features, specifically the extent of the primary and secondary separation zones that occur in square sudden expansions, being frequently used in ventilation systems. To address this gap in the literature, an extensive set of numerical simulations, validated to LDA and pressure measurements, has been carried out for the realistic case of fully developed turbulent inlet flow. The simulations systematically investigate the extent of the secondary separation zone and the reattachment length for an area ratio range of n_{AR} = 1.5 – 6.4 and a Reynolds number range of Re_1 = (0.09 – 3.0)·10^5, being representative of ventilation systems. The primary separation zone is characterized by energetic backflows, which can adversely affect the accuracy of flow measuring units, and controlling ability of devices such as valves and dampers. Thus, the downstream location of the primary separation zone, i.e., the reattachment length, determines the minimum distance required for the reasonable installation of flow measuring or control devices in air ducts. The secondary separation zone is characterized by slow-moving fluid, increasing the likelihood of the accumulation of contaminants and pathogens in the ventilation duct. Therefore, the extent of the secondary separation zone provides valuable information on the appropriate placement of cleaning hatches.

CONTRIBUTION #1 – flow features in square sudden expansions

The maximum and mean extent of the secondary separation zone and the minimum, maximum, and mean reattachment lengths, developing in square sudden expansions, are given in Table T1.1. The geometry and the flow features are depicted in Fig. T1.1. The physical assumptions and the ranges of validity are provided in Table T1.2, for which the related equations are shown in Eqs. (T1.1) – (T1.3). The list of symbols is summarized in Table T1.3.

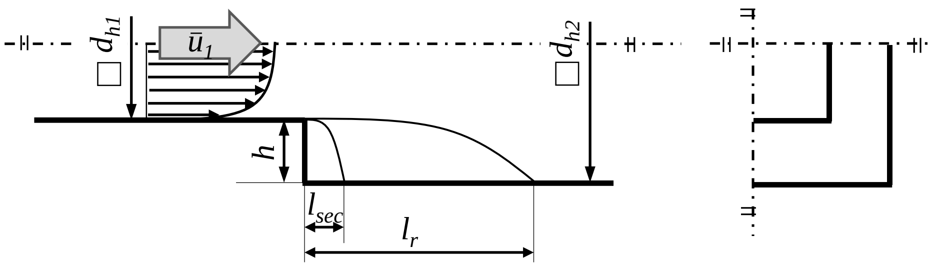

Fig. T1.1 Geometry of the square sudden expansion and schematic drawing of the developing flow features.

Table T1.1 Flow features in square sudden expansions.

	minimum	maximum	mean
Secondary separation (l_{sec})		1 – 6h	1 – 2h
Reattachment length (l_r)	5 – 10h	15 – 42h	8 – 16h

Table T1.2 Physical assumptions and ranges of validity.

Name	**Description**
Nature of flow	single-phase, stationary, adiabatic, turbulent
Material properties	constant density and viscosity
Rheology	Newtonian
Geometry	square sudden expansion
Wall roughness	hydraulically smooth
Inlet flow	fully developed
n_{AR}	1.5 – 6.4
Re_1	$(0.09 – 3.0)\cdot 10^5$

$$A_1 = d_{h1}^2;\ A_2 = d_{h2}^2 \tag{T1.1}$$

$$n_{AR} = \frac{A_2}{A_1} \tag{T1.2}$$

$$Re_1 = \frac{\overline{u}_1 \cdot d_{h1}}{\nu} \tag{T1.3}$$

Table T1.3 List of symbols.

Letters		
A	cross-sectional area of the duct	m^2
d_h	hydraulic diameter of the duct	m
h	step height	m
l_{sec}	length of the secondary separation zone	m
l_r	reattachment length	m
n_{AR}	area ratio	1
Re	Reynolds number	1
$\overline{u}$	area-averaged streamwise velocity	m/s
ν	kinematic viscosity of the fluid	m^2/s
Subscripts		
1	upstream of the expansion plane	
2	downstream of the expansion plane	

Related publications: [P1], [P2], [P3]

Accurate calculation of the hydraulic resistance of air duct components inherently contributes to the creation of energetically more efficient ventilation systems, a primary concern in contemporary building construction. Hence, the method of calculating the loss coefficient of square sudden expansions – a frequent element in ventilation ductworks – has been refined, enabling a more reliable design and operation of ventilation systems. Existing calculation methods available in the literature have been critically evaluated and supplemented in a comprehensive manner. An extensive set of numerical simulations, validated to LDA and pressure measurements, have been conducted for the realistic case of fully developed turbulent inlet flow. The loss coefficients provided by the numerical simulations are considered as baseline values for assessing the accuracy of the semi-empirical method. The systematic examination focuses on the loss coefficient within an area ratio range of n_{AR} *= 1.5 – 6.4 and a Reynolds number range of* Re_1 *= (0.09 – 3.0)·10*^{5}*, being representative of ventilation systems. The novelty of this calculation method lies in its extension of the applicability of descriptive equations, which were previously sporadically available in the literature for circular cross-sections, to now include square ducts. These equations have been developed into a novel comprehensive workflow for enabling easily executable calculations, supplemented with a quantitative validity analysis.*

CONTRIBUTION #2 – loss coefficient of square sudden expansions

A semi-empirical model provided in Eq. (T2.8) is proposed for calculating the loss coefficient of square sudden expansions for the case of fully developed turbulent inlet flow. The calculation inputs, workflow, and output are provided by Eqs. (T2.1) – (T2.3), Eqs. (T2.4) → (T2.7) and Eq. (T2.8), respectively. The geometry of the square sudden expansion and the input parameters are depicted in Fig. T2.1. The physical assumptions and the ranges of validity are provided in Table T2.1. For these ranges, the estimated absolute uncertainty of the semi-empirical loss coefficient is given in Fig. T2.2. The list of symbols is summarized in Table T2.2.

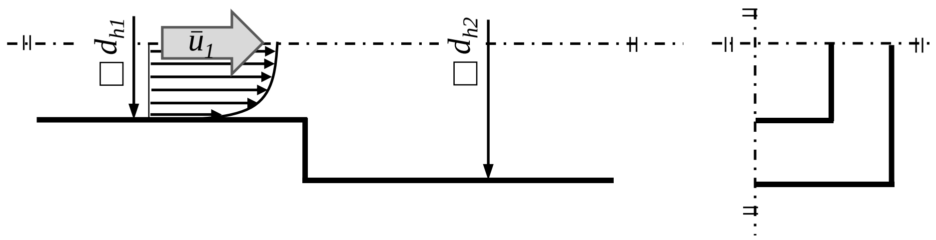

Fig. T2.1 Geometry of the square sudden expansion and input parameters.

INPUT DATA:

$$A_1 = d_{h1}^2;\ A_2 = d_{h2}^2 \quad \text{(T2.1)}$$

$$n_{AR} = \frac{A_2}{A_1} \quad \text{(T2.2)}$$

$$Re_1 = \frac{\bar{u}_1 \cdot d_{h1}}{\nu} \quad \text{(T2.3)}$$

WORKFLOW:	
$$\frac{1}{\sqrt{\lambda_1}} = 2 \cdot log\left(Re_1\sqrt{\lambda_1}\right) - 0.8$$	(T2.4)
$$\mu \approx \frac{1}{\sqrt{\lambda_1}}$$	(T2.5)
$$M = \frac{(2\mu+1)^2(\mu+1)}{4\mu^2(\mu+2)}$$	(T2.6)
$$N = \frac{(2\mu+1)^3(\mu+1)^3}{4\mu^4(\mu+3)(2\mu+3)}$$	(T2.7)
OUTPUT DATA:	
$$\zeta_{BC} = \frac{\Delta p_{BC}}{\frac{\rho}{2}\bar{u}_1^2} = N - \frac{2M}{n_{AR}} + \frac{2M-N}{n_{AR}^2}$$	(T2.8)

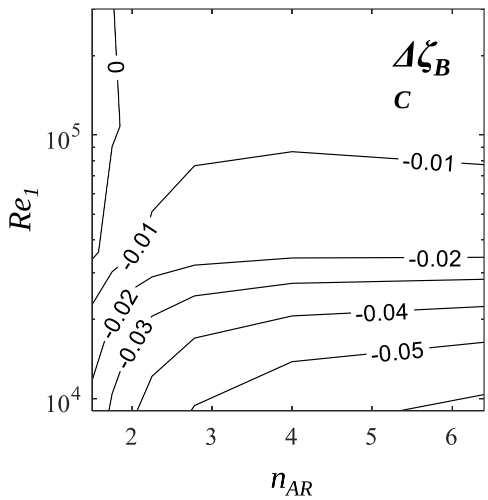

Fig. T2.2 Absolute uncertainty of the semi-empirical loss coefficient.

Table T2.1 Physical assumptions and ranges of validity.

Name	**Description**
Nature of flow	single-phase, stationary, adiabatic, turbulent
Material properties	constant density and viscosity
Rheology	Newtonian
Geometry	square sudden expansion
Wall roughness	hydraulically smooth
Inlet flow	fully developed
n_{AR}	1.5 – 6.4
Re_1	$(0.09 – 3.0)\cdot 10^5$

Table T2.2 List of symbols.

Letters		
A	cross-sectional area of the duct	m^2
d_h	hydraulic diameter of the duct	m
M	momentum coefficient	1
N	kinetic energy coefficient	1
n_{AR}	area ratio	1
Δp_{BC}	total pressure loss of the square sudden expansion	Pa
Re	Reynolds number	1
$\overline{u}$	area-averaged streamwise velocity	m/s
ζ_{BC}	loss coefficient of the square sudden expansion	1
$\Delta\zeta_{BC}$	absolute uncertainty of the loss coefficient of the square sudden expansion	1
λ	pipe friction coefficient	1
μ	profile shape factor	1
ν	kinematic viscosity of the fluid	m^2/s
ρ	density of the fluid	kg/m^3
Subscripts		
1	upstream of the expansion plane	
2	downstream of the expansion plane	

Related publications: [P1], [P2], [P3], [P4]

The method of calculating the static pressure recovery coefficient of square sudden expansions has been refined, enabling a more reliable design of ventilation systems. Existing calculation methods available in the literature have been critically evaluated and supplemented in a comprehensive manner. An extensive set of numerical simulations, validated to LDA and pressure measurements, have been conducted for the realistic case of fully developed turbulent inlet flow. The static pressure recovery coefficients provided by the numerical simulations are considered as baseline values for assessing the accuracy of the semi-empirical method. The systematic examination focuses on the static pressure recovery coefficient within an area ratio range of n_{AR} *= 1.5 – 6.4 and a Reynolds number range of* Re_1 *= (0.09 – 3.0)·10*^{5}*, being representative of ventilation systems. The novelty of this calculation method lies in its extension of the applicability of descriptive equations, which were previously sporadically available in the literature for circular cross-sections, to now include square ducts. These equations have been developed into a novel comprehensive workflow for enabling easily executable calculations, supplemented with a quantitative validity analysis. Additionally, the research has been supplemented with an analytical evaluation of the static pressure recovery equations, which establishes the existence of an optimum area ratio at* n_{AR} *= 2 for the best performance of the sudden expansion when considered as a diffuser. This analysis has been found to be lacking in the literature.*

CONTRIBUTION #3 – static pressure recovery coefficient of square sudden expansions

A semi-empirical model provided in Eq. (T3.7) is proposed for calculating the static pressure recovery coefficient of square sudden expansions in the case of fully developed turbulent upstream flow. The calculation inputs, workflow, and output are provided by Eqs. (T3.1) – (T3.3), Eqs. (T3.4) → (T3.6) and Eq. (T3.7), respectively. The geometry of the square sudden expansion and the input parameters are depicted in Fig. T3.1. The physical assumptions and the ranges of validity are provided in Table T3.1. For these ranges, the absolute uncertainty of the semi-empirical static pressure recovery coefficient is given in Fig. T3.2. The list of symbols is summarized in Table T3.2.

Based on the partial derivation of the static pressure recovery coefficient – given in Eq. (T3.7) – with respect to the area ratio – as provided in Eqs. (T3.8) – (T3.9) –, and also supported by the results of the numerical simulations, a square sudden expansion yields maximum static pressure recovery at an area ratio of n_{AR} = 2.

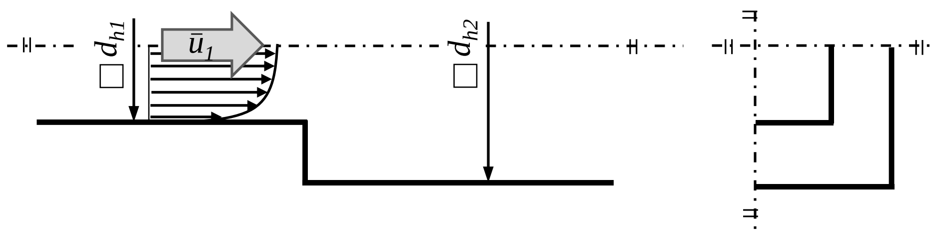

Fig. T3.1 Geometry of the square sudden expansion and input parameters.

INPUT DATA:

$$A_1 = d_{h1}^2;\ A_2 = d_{h2}^2 \quad \text{(T3.1)}$$

$$n_{AR} = \frac{A_2}{A_1} \quad \text{(T3.2)}$$

$$Re_1 = \frac{\overline{u}_1 \cdot d_{h1}}{\nu} \quad \text{(T3.3)}$$

WORKFLOW:

$$\frac{1}{\sqrt{\lambda_1}} = 2 \cdot log\left(Re_1\sqrt{\lambda_1}\right) - 0.8 \quad \text{(T3.4)}$$

$$\mu \approx \frac{1}{\sqrt{\lambda_1}} \quad \text{(T3.5)}$$

$$M = \frac{(2\mu + 1)^2(\mu + 1)}{4\mu^2(\mu + 2)} \quad \text{(T3.6)}$$

OUTPUT DATA:

$$c_{SPR} = \frac{\Delta p_{SPR}}{\frac{\rho}{2}\overline{u}_1^2} = \frac{2M}{n_{AR}} - \frac{2M}{n_{AR}^2} \quad \text{(T3.7)}$$

ANALYTICAL LOCUS OF MAXIMUM $c_{SPR,emp}$

$$\frac{\partial c_{SPR}}{\partial n_{AR}} = 0 \leftrightarrow n_{AR} = 2 \quad \text{(T3.8)}$$

$$\left.\frac{\partial^2 c_{SPR}}{\partial n_{AR}^2}\right|_{n_{AR}=2} < 0 \quad \text{(T3.9)}$$

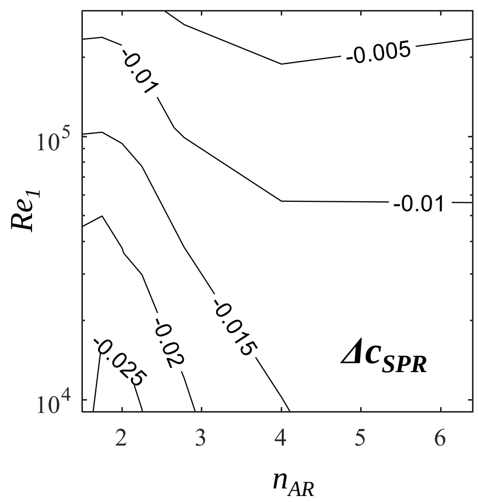

Fig. T3.2 Absolute uncertainty of the semi-empirical static pressure recovery coefficient.

Table T3.1 Physical assumptions and ranges of validity.

Name	**Description**
Nature of flow	single-phase, stationary, adiabatic, turbulent
Material properties	constant density and viscosity
Rheology	Newtonian
Geometry	square sudden expansion
Wall roughness	hydraulically smooth
Inlet flow	fully developed
n_{AR}	1.5 – 6.4
Re_1	$(0.09 – 3.0)\cdot 10^5$

Table T3.2 List of symbols.

Letters		
A	cross-sectional area of the duct	m^2
c_{SPR}	static pressure recovery coefficient of the square sudden expansion	1
Δc_{SPR}	absolute uncertainty of the static pressure recovery coefficient of the square sudden expansion	1
d_h	hydraulic diameter of the duct	m
M	momentum coefficient	1
n_{AR}	area ratio	1
Δp_{SPR}	static pressure recovery of the square sudden expansion	Pa
Re	Reynolds number	1
$\overline{u}$	area-averaged streamwise velocity	m/s
λ	pipe friction coefficient	1
μ	profile shape factor	1
ν	kinematic viscosity of the fluid	m^2/s
ρ	density of the fluid	kg/m^3
Subscripts		
1	upstream of the expansion plane	
2	downstream of the expansion plane	

Related publications: [P2], [P3]

Mechanical ventilation in buildings is a key contributor to the significant energy consumption of the construction industry; therefore, rational energy management in ventilation systems plays a major role in promoting the energy efficiency of buildings. To address the fluid mechanical losses associated with square sudden expansions – and thus, with the overall energy expenditure of ventilation ducts – a novel passive flow control method, termed the miniflap method, has been developed. For the assessment of the effectiveness of the miniflap method, an extensive set of numerical simulations, validated to LDA and pressure measurements, has been conducted. The simulations focused on the realistic case of a fully developed turbulent inlet flow and systematically examined the loss coefficient of square sudden expansion equipped with miniflaps across various parameter ranges. These ranges included a miniflap length of l_{mf}/d_{h1} *= 0 – 0.5 →* l_{mf}/h *= 0 – 2.4, a miniflap angle of* α *= 6° – 18°, an area ratio of the sudden expansion of* n_{AR} *= 2 – 6.4, and a Reynolds number range of* Re_1 *= (0.36 – 3.0)·10*^{5}*. The results of the study demonstrated that the miniflap method performed competitively compared to existing pyramidal diffusers, achieving comparable loss coefficient values while requiring a significantly shorter axial extent and easy-to-manufacture geometry.*

CONTRIBUTION #4 – loss coefficient of square sudden expansions equipped with miniflaps

A passive flow control method, termed as miniflap method, is proposed for reducing the losses of square sudden expansions. The miniflaps are short, rectangular sheets placed at the step edge of the sudden expansion, acting as a continuation of the upstream duct wall. The sketch of the geometry of a square sudden expansion equipped with miniflaps is shown in Fig. T4.1. The geometry and the input parameters are depicted in Fig. T4.2, the physical assumptions and the ranges of validity are provided in Table T4.1, and the list of symbols is summarized in Table T4.2.

The optimal angle of the miniflaps, associated with the minimum value of the loss coefficient, is given by Eq. (T4.1). In order to calculate the loss coefficient of a square sudden expansion at an optimal miniflap angle setup as a function of the miniflap length, a set of model equations is provided in Eqs. (T4.2) – (T4.7). The optimal length of the miniflaps for the optimal miniflap angle setup is given by Eq. (T4.8). A correlation of the corresponding loss coefficient at an optimal miniflap configuration is given in Eq. (T4.9).

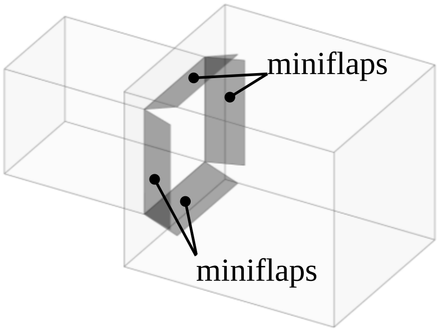

Fig. T4.1 Square sudden expansion equipped with miniflaps.

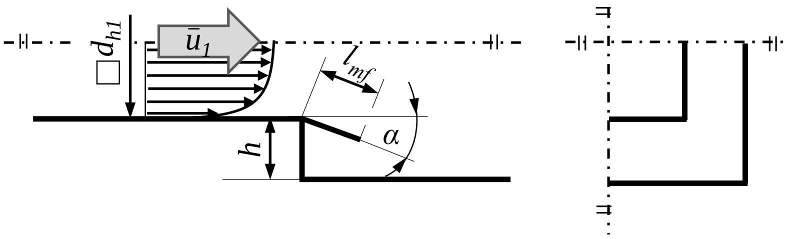

Fig. T4.2 Geometry of the square sudden expansion equipped with miniflaps and input parameters.

OPTIMAL MINIFLAP ANGLE

$$\alpha_{opt} = 10° \pm 2° \tag{T4.1}$$

MODEL EQUATIONS FOR LOSS CALCULATION AT $\boldsymbol{\alpha_{opt}}$

$$\zeta_{MF,\alpha_{opt}} = \zeta_{BC} \cdot \left(a \cdot e^{-b \cdot l_{mf}/h} + c\right) \tag{T4.2}$$

$$a = 0.0217 \cdot Re_1^{0.200} \tag{T4.3}$$

$$b = 0.253 \cdot Re_1^{0.246} \tag{T4.4}$$

$$c = 1.56 \cdot Re_1^{-0.0602} \tag{T4.5}$$

$$\zeta_{BC} = N - \frac{2M}{n_{AR}} + \frac{2M - N}{n_{AR}^2} \tag{T4.6}$$

$$Re_1 = \frac{\overline{u}_1 \cdot d_{h1}}{\nu} \tag{T4.7}$$

OPTIMAL MINIFLAP LENGTH

$$l_{mf,opt} = 1h \tag{T4.8}$$

MODEL EQUATION FOR LOSS CALCULATION AT $\boldsymbol{\alpha_{opt}}$, $\boldsymbol{l_{mf,opt}}$

$$\zeta_{MF,opt} = \zeta_{BC} \cdot 1.56 \cdot Re_1^{-0.0602} \tag{T4.9}$$

Table T4.1 Physical assumptions and ranges of validity.

Name	Description
Nature of flow	single-phase, stationary, adiabatic, turbulent
Material properties	constant density and viscosity
Rheology	Newtonian
Geometry	square sudden expansion
Wall roughness	hydraulically smooth
Inlet flow	fully developed
n_{AR}	1.5 – 6.4
Re_1	(0.09 – 3.0)·10^5
l_{mf}/h	0 – 2.4

Table T4.2 List of symbols.

Letters		
a, b, c	parameters of the model equation	m^2
d_h	hydraulic diameter of the duct	m
h	step height	m
l_{mf}	miniflap length	m
M	momentum coefficient	1
N	kinetic energy coefficient	1
n_{AR}	area ratio	1
Re	Reynolds number	1
$\overline{u}$	area-averaged streamwise velocity	m/s
α	miniflap angle	degree
ζ	loss coefficient	1
ν	kinematic viscosity of the fluid	m^2/s
Subscripts		
1	upstream of the expansion plane	
2	downstream of the expansion plane	
BC	Borda-Carnot expansion without miniflaps	
MF	Borda-Carnot expansion with miniflaps	
opt	optimal	

Related publications: [P1], [P2], [P3], [P4], [P5], [P6], [P7]

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