

Conditioning of swirling and stratified pipe-flow: Analysis with laser-Doppler velocimetry

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Abstract

Flow conditioning can be used for eliminating swirl, restoring flow symmetry, and generating a repeatable, fully developed flow profile upstream from flow measurement devices. In particular, the conditioning with tube bundles and straightening vanes has found many applications in flow metering. In this article, we use laser-Doppler velocimetry (LDV) to analyze flow profiles downstream from three different flow conditioners – a tube bundle conditioner, a Spearman conditioner, and a Zanker conditioner. We study the performance of these three devices with respect to conditioning swirling and thermally stratified pipe flows. For a quantitative comparison, we use selected performance indicators measuring the profile flatness, the asymmetry of the profile, the swirl angle of the secondary flow, and the turbulence intensity in the core region with respect to a fully developed reference profile. We find that the Zanker conditioner performs best for decreasing the swirl angle, whereas flow profiles downstream from the Spearman conditioner and the tube bundle conditioner show higher secondary velocities at locations close to the wall. For the conditioning of thermally stratified asymmetric flow profiles, the utilized flow conditioners provide unfavorable results. None of the conditioners is able to fully restore a symmetric and fully developed flow profile in thermally stratified flow.

1. Introduction

To positively modify flow disturbances caused by installation effects, flow conditioning, straightening or diffusion can be used for eliminating swirl, restoring flow symmetry, and generating a repeatable, fully developed flow profile. In general, flow conditioning with tube bundles and straightening vanes has found many applications in liquid and gas measurement systems as well as in ultrasonic flow metering [1]. Many different standard flow conditioners are presently available and performance was tested in various studies [2–5]. A summary of available information on the flow conditioner performance under different process conditions is provided in Table 1. Tube bundle conditioner and the perforated plates are expected to have similar performance, while the screens are expected to have lower performance in improving swirling flow. An ideal flow conditioner should be effective in a wide range of Reynolds numbers (Re). However, the behaviour of different devices may change significantly as the wall roughness and fluid viscosity of the application changes and recent studies suggest that in viscous fluids, tube bundle conditioners can have significantly higher pressure drops than perforated plate flow conditioners [1]. Further, increasing the length of conditioners like tube bundles or increasing the thickness of conditioner plates does not necessarily improve conditioning efficiency [1]. Perforated plates are the most commonly used type of flow straighteners. Examples of this type include the flow conditioners by Laws [6, 7], Spearman

[8], and Gallagher [9], in addition to the thick-plate version of the Zanker straightener [10, 11]. These perforated plates with circular passages are considered the current state of the art but still have certain known deficiencies. Yet, attempts to use plates of higher porosity and hence lower pressure loss may result in a reduction in flow conditioning performance [12]. The perforated plates have a porosity of about 50.0% (Spearman: 47.5%, Zanker: 45.0%, and Laws: 51.6% [8, 13]). Besides the porosity, other geometrical parameters, such as diameter, number of holes, and their arrangement, also may have an important influence the capability to restore a fully developed flow [14].

Table 1: Available information on flow conditioner performance [5].

Flow conditioner	Pressure loss	Swirling flow	Fluid stratification	Temp. stratification
Multi-body	high	high	-	-
Perforated plates	high	high	low	low
Tube bundle	high	high	low	low
Screens	high	medium	low	low

In view of the different available investigations [1–14], we choose to conduct LDV experiments with the tube bundle conditioner, the Spearman conditioner, and the Zanker conditioner (Figure 1). The tube bundle conditioner exhibits a lower pressure drop and previous investigations suggests a relatively fast decay of the swirl angle [15, 16]. However, for restoring a normal turbulence intensity, the tube bundle conditioner is expected to perform less effectively than others [17]. The Spearman conditioner is selected because of a good

expected performance in diminishing flow disturbances and due to the more favorable expected performance when comparing the results with the Laws, the Mitsubishi, and the Akashi conditioner for which an asymmetry in the flow may persist [16, 8]. The Zanker conditioner is chosen to be investigated as it is commonly used but available research data is lacking.

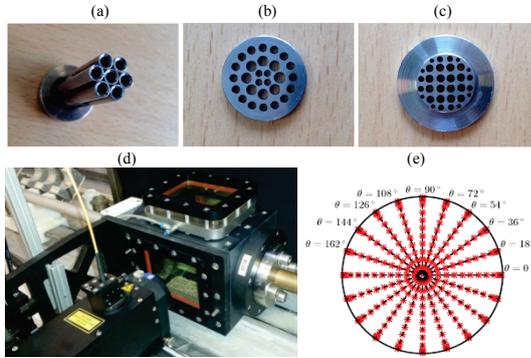


Figure 1: Different flow conditioners: Tube bundle (a), Spearman (b) [16], Zanker (c) [13]; LDV window chamber (d), and LDV measurement grid (e).

2. Materials and methods

We use a commercial Nd:YAG laser-Doppler velocimetry (LDV) probe from ILA/Optolution with a window chamber that enables full three-dimensional optical access. The probe is mounted on a traversing system for automated displacement in a Cartesian coordinate system (Figure 1 (d) and (e)). We perform all experiments on a verification and calibration test bench in the flow laboratory of Kamstrup A/S using brass pipes of inner diameter $D = 15.0$ mm (DN15). The volumetric flow rate Q , the water temperature T , and the pressure p are actively controlled and adjusted within a PID feedback loop. For qualitative comparison, the flow profiles are visualized in 2D contour plots and individual profile paths as indicated in Figure 1 (e). For quantitative comparisons, we use performance indicators [18]. Performance indicators are integral metrics to measure the shape of profiles and to quantify the deviation from reference profiles such as the Gersten and Herwig [19] profile for turbulent flow or the Poiseuille profile for laminar flow. The established limits for admissible ranges of the performance indicators of a fully developed profile are:

$$\begin{aligned} \text{Swirl angle:} & \quad \phi_{\max} = 2.0^\circ \\ \text{Profile factor } K_p: & \quad 0.8 \leq K_p \leq 1.3 \\ \text{Asymmetry factor } K_a: & \quad K_{a,\max} = 1.0 \% \\ \text{Turbulence factor } K_{Tu}: & \quad K_{Tu,\max} = 2.0 \end{aligned}$$

We compute performance indicators for all profile paths and report averaged values along with standard deviations indicated as error bars in the corresponding graphics.

3. Flow conditioning experiments

As a baseline experiment, all flow conditioners are evaluated in undisturbed flow. Ideally, the effect of the conditioners on undisturbed turbulent pipe-flow should be negligible. However, manufacturing uncertainties or

deviations might influence the velocity profiles. Consequently, a baseline investigation of flow conditioners in undisturbed flow is necessary. In undisturbed flow, all considered conditioners provide flow conditions that comply with the established limits of K_p , K_a , and K_{Tu} (Table 2, profiles not shown due to space limitations). However, only the Zanker conditioner provides swirl angles below 2.0° . The tube bundle and the Spearman conditioner introduce weakly swirling flows. The present samples provide reasonable baseline results. However, this investigation shows that the flow conditioners might introduce disturbances because of manufacturing uncertainties and a performance better than the baseline performance should not be expected.

Table 2: Performance indicators for different flow conditioners in undisturbed flow.

	K_p (-)	K_a (%)	K_{Tu} (-)	ϕ ($^\circ$)
Spearman	1.075	0.577	1.479	2.64
Zanker	1.130	0.699	1.496	1.46
Tube bundle	0.847	0.702	1.137	2.90

3.1 Conditioning of swirling flow

Swirling flow is generated with a standardized swirl disturbance generator with inner diameter $D = 15.0$ mm used in type testing of water, heat, and cooling meters [20, 21]. For all experiments with swirling flow, we use a flow-rate of $Q = 1.705$ m³/h and a water temperature of 20.0 °C corresponding to $Re = 4.0 \cdot 10^4$, where Re is based on the diameter D and the volumetric velocity $w_{vol} = Q/A$. The location of the swirl disturbance generator is approximately $100.0D$ downstream from the inlet of the flowbench to ensure undisturbed fully developed flow upstream (Figure 2). The distance z_{CSW} between the swirl disturbance generator and the flow conditioner is varied between $2.0D$, $10.0D$ and $22.0D$ such that the flow conditioner is exposed to different flow profiles and different swirling intensities. All LDV measurements are conducted $12.0D$ downstream from the flow conditioner.

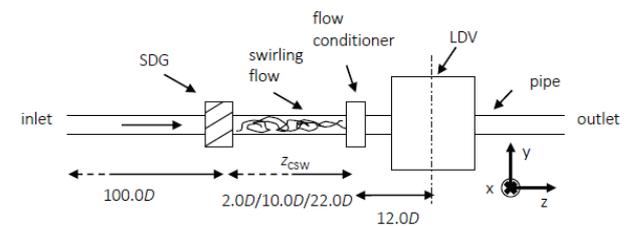


Figure 2: Experimental setup of the flow conditioning in swirling flow generated with a standardized swirl disturbance generator (SDG).

3.2 Conditioning of the axial velocity profile

All profile factors K_p are within the admissible range (Table 3). While the conditioners show similar values at $z_{CSW} = 2.0D$ and $z_{CSW} = 10.0D$, the Spearman conditioner shows higher values than the Zanker conditioner at $z_{CSW} = 22.0D$. The Zanker conditioner provides values close to $K_p = 1$ at the smallest and the largest distance, indicating full compliance with the Gersten and Herwig profile [19]. The Spearman conditioner provides values around $K_p = 1$ only at the smallest z_{CSW} , while K_p is found

to increase towards values > 1 for larger separation distances. This indicates that larger separation distances lead to profiles with more pronounced peaks in the pipe. The results of the tube bundle conditioner show lower profile factors, which characterize a flat profile ($K_p < 1$). This flatness remains nearly constant for all separation distances (Figure 3 (m)–(o)). The velocity contours show a large symmetric region with constant velocity in the center of the pipe, indicating a flatter profile compared to the smaller and more asymmetric region of constant velocity for a more peaky profile using the Spearman and the Zanker conditioner (Figure 3).

For all conditioners, the asymmetry factor K_a exceeds the threshold $K_{a,max}$ at the intermediate separation distance $z_{CSW} = 10.0D$, while values within the admissible limits are achieved for the small and large separation distances. The differences in asymmetry are visible through the displacement of individual profiles (Figure 3 (h)) and through a displacement of the centroid in the 2D contour plots (Figure 3 (k)). According to Schlüter and Merzkirch [16], the Laws conditioner, which is related to the Spearman conditioner, is expected to produce a high degree of symmetry, while the tube bundle conditioner is expected to be less effective. This inefficiency of the tube bundle is confirmed by the study of Wendt et al. [17]. In the present study, both the Spearman and the tube bundle conditioner are effective at $2.0D$ and $22.0D$.

Table 3: Performance indicators for different flow conditioners in swirling flow at different separation distances.

	K_p (-)	K_a (%)	K_{Tu} (-)	ϕ ($^\circ$)
Spearman				
2D	1.0470	0.7099	1.5130	2.92
10D	1.1406	1.0480	1.5200	3.13
22D	1.1384	0.8270	1.5354	2.83
Zanker				
2D	1.0035	0.5440	1.5340	2.34
10D	1.1660	1.5130	1.6650	2.16
22D	1.0117	0.3704	1.5320	1.92
Tube bundle				
2D	0.8910	0.6880	1.3170	2.11
10D	0.8880	1.1190	1.2820	1.75
22D	1.0460	0.7690	1.2570	2.32

3.3 Conditioning of the secondary flow

For the Spearman conditioner, the swirl angle exceeds ϕ_{max} for all separation distances z_{CSW} . Visual inspection of the secondary flow $\bar{v}_{xy} = \sqrt{v_x^2 + v_y^2}$ confirms this observation (Figure 4 (a)–(f)). The exceeded swirl angle is caused by high secondary flow close to the wall (Figure 4 (d)–(f)). The Zanker conditioner shows an improvement of the swirl angle with increasing z_{CSW} , reaching a value of $\phi = 1.92^\circ$ at $z_{CSW} = 22.0D$. A monotonic decrease in the intensity of the secondary flow is shown in the velocity profiles (Figure 4 (g)–(i)). The secondary flow close to the wall shows high values at $z_{CSW} = 2.0D$. Conversely, these regions disappear for $z_{CSW} = 22.0D$. For the tube bundle conditioner, the swirl angle is non-monotonic for different z_{CSW} (Table 3). The swirl angle reaches a value of 2.11° at $2.0D$, further decreases for the intermediate z_{CSW} (1.75°) but increases again for $z_{CSW} = 22.0D$ (2.32°).

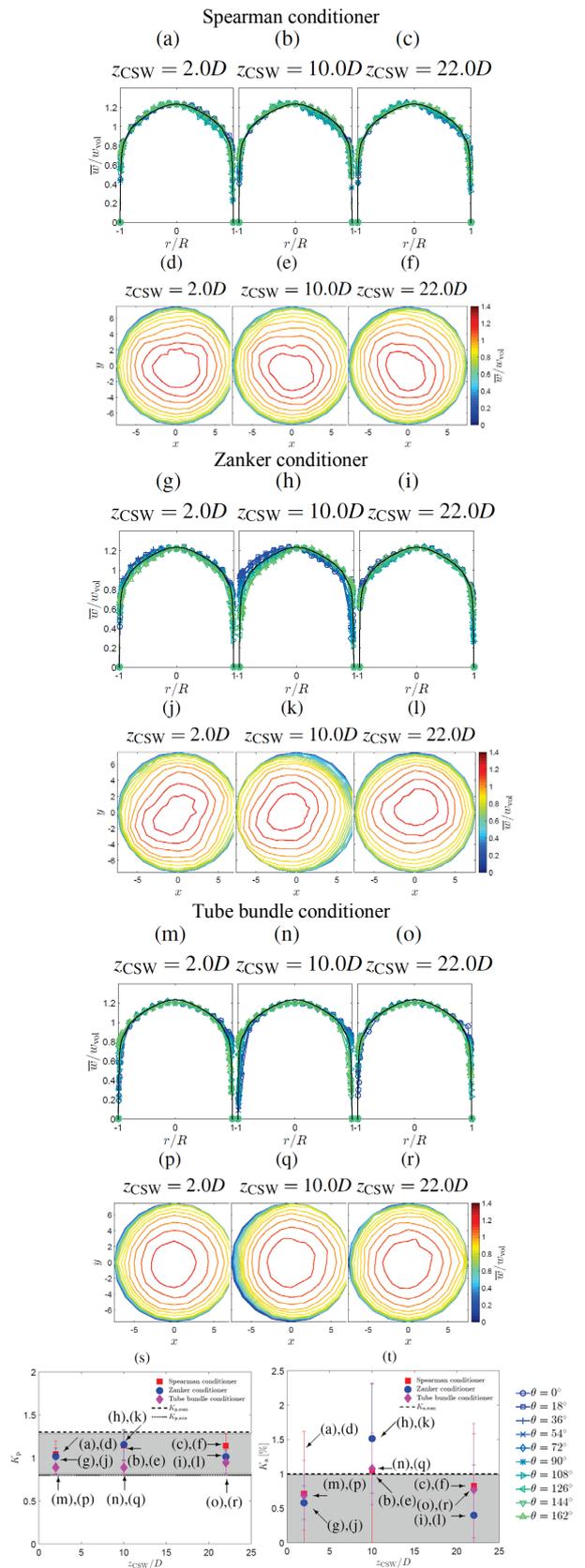


Figure 3: Contour plots and individual profiles of the axial velocity (a)–(r) along with comparison of profile factors K_p (s) and asymmetry factors K_a (t) at various separation distances.

For $z_{CSW} = 2.0D$, a relatively high radial velocity is found at the pipe center, which vanishes for $z_{CSW} = 10.0D$ and for $z_{CSW} = 22.0D$ (Figure 4 (m)–(r)). The high peaks in \bar{v}_{xy} at the wall result for the intermediate and long z_{CSW} while

the short z_{CSW} has no high secondary velocities close to the wall but an overall high secondary velocity.

The most important parameters influencing the performance of flow straighteners is the arrangement of holes, the porosity, and the thickness of the conditioner. Overall, the Zanker conditioner provides the most favorable swirl angles and secondary flow profiles. However, the Zanker conditioner has a lower porosity than the Spearman conditioner, and therefore provides a higher pressure drop.

Due to different boundary conditions, the comparability among independent studies is limited. The present results are in good agreement with the conclusion of Deane [5] who finds that perforated plates and tube bundle conditioners have a high efficiency in reducing swirl disturbances. However, in an investigation with air as working fluid, Schlüter and Merzkirch [16] find a lower efficiency of the tube bundle conditioner in attenuating disturbances compared to perforated plates, which is not confirmed in the present investigation. The differences between the present study and Schlüter and Merzkirch [16] could be related to the different boundary conditions and working fluids. For example, Schlüter and Merzkirch [16] generate disturbances with a double bend-out of plane, whereas the present study uses a swirl disturbance generator. Spearman et al. [8] find an undisturbed flow from $11.0D$ downstream and onwards, where the disturbance is generated with a single-bend configuration $4.0D$ upstream from the Spearman conditioner. Xiong et al. [15] find practically vanishing swirl angles for the tube bundle, the Laws conditioner, and the Akashi conditioner already at $1.5D$ downstream from the conditioners, where the disturbance is generated $2.0D$ upstream with a double-bend out of plane. In contrast, the present results indicate that the 2° limit is still not reached at $12.0D$ downstream from the Spearman and tube bundle conditioners, even for the maximal separation distance between disturbance generator and conditioner. Laribi et al. [3] find a decrease of $1/5$ of the swirl angle at $6.0D$ downstream from a tube bundle conditioner, where the disturbances are generated $4.5D$ upstream with a double-bend out of plane. This is in good agreement with the present results.

3.4 Conditioning of turbulence intensity

All conditioners provide turbulence factors within the admissible range. The Spearman and the Zanker conditioner have similar turbulence intensities of $K_{Tu} \approx 1.7$ for the short and the intermediate distance, while the Spearman conditioner provides a higher turbulence factor at $z_{CSW} = 22.0D$ (Table 3 and Figure 5). The tube bundle conditioner exhibits lower turbulence factors of $K_{Tu} \approx 1.2$ (Table 3). The turbulence intensity Tu_{max} in the pipe center ($r/R = \pm 0.2$) takes the lowest values of approximately 4.0% for the tube bundle conditioner (not shown). The profile of the turbulence intensity is flatter for the tube bundle conditioner compared to the Spearman and the Zanker conditioner, which characterizes a lower gradient in Tu within $r/R = \pm 0.2$ (not shown).

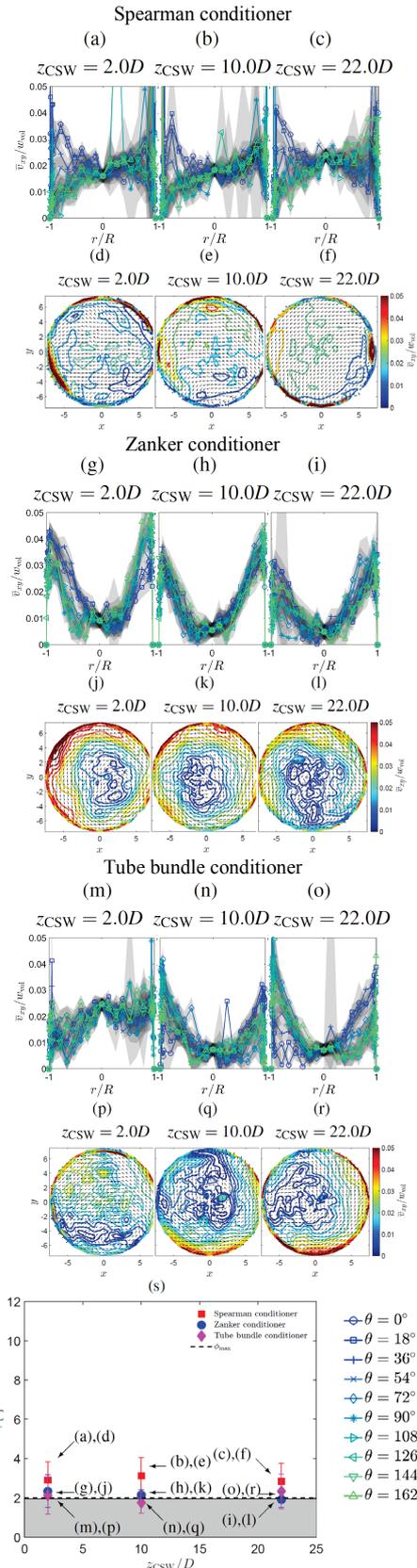


Figure 4: Contour plots and individual profiles of the secondary flow (a)–(r) along with comparison of the swirl angle ϕ (s) at various separation distances using the three conditioners.

The weaker efficiency of tube bundles to condition the turbulence intensity compared to other conditioners (see, for example Wendt et al. [17], Laribi et al. [3], and Xiong et al. [15]) is not confirmed in the present study.

However, the present study is realized with $D = 15.0$ mm pipe diameter whereas Wendt et al. [17] use DN200 pipes and Laribi et al. [3] and Xiong et al. [15] use DN100 pipes which might explain differences in turbulence levels. Further differences in the working fluid and other boundary conditions might well add to differences in results.

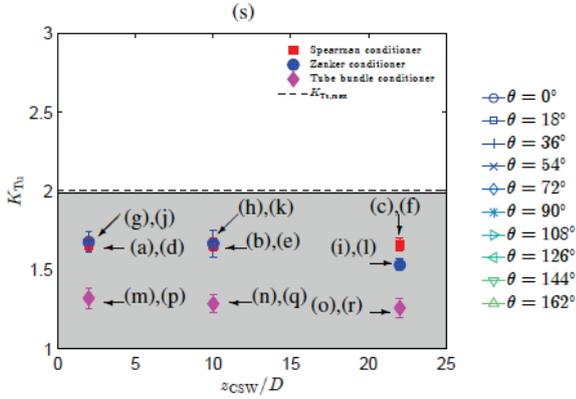


Figure 5: Comparison of the different turbulence factors K_{Tu} at various separation distances. (The letters (a)–(r) refer to additional figures of the turbulence intensity profiles that cannot be shown in this article due to space limitations.)

3.5 Conditioning of stratified flow

Stratified asymmetric flows emerge for high temperatures and low Reynolds numbers. We generate stratified flow with a water temperature of $T = 60$ °C and a flow rate of $Q = 0.0235$ m³/h resulting in a Reynolds number of $Re = 1.0 \cdot 10^3$. The pipes are not insulated to provide an experimental setup with maximized heat exchange between the fluid, the pipe, and the environment (Figure 9). We perform two measurements at $z_{CSt} = 5.0D$ and at $z_{CSt} = 110.0D$. The measurement close to the inlet at $5.0D$ is added to see the influence of the flow conditioners on the pipe-flow in a case in which the stratification is less developed.

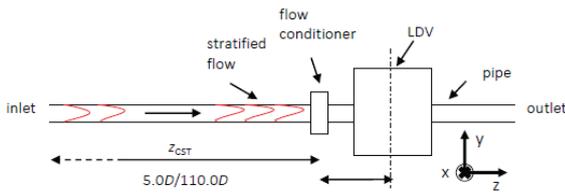


Figure 9: Configuration of the flow conditioning measurements for a stratification pipe-flow.

In comparison with the unconditioned stratified profiles (not shown), the maximum velocity is lower and the stratification is less pronounced for all three conditioners (Figure 6). For the Spearman conditioner, the stratification is more developed for the longer separation distance (Figure 6 (a) and (b)). For $z_{CSt} = 110.0D$, the profile at $\theta = 0^\circ$ shows a flat shape and reaches a maximum value of $\bar{w}/w_{vol} \approx 1.4$, while the peak is $\bar{w}/w_{vol} \approx 1.6$ at $\theta = 90^\circ$. For $z_{CSt} = 5.0D$, the different profiles exhibit similar velocities with a less developed stratification. The Zanker conditioner yields very similar profiles for the two separation distances. Both velocity profiles still exhibit elevated peaks and strongly stratified flow (Figure 6 (e)–(h)). The performance indicators K_a

are higher compared to the Spearman conditioner (Table 4). The tube bundle conditioner provides lower asymmetry factors than the other conditioners and therefore a better conditioning of stratification. The maximum velocity is $\bar{w}/w_{vol} \approx 1.4$, which indicates a flat profile with profile factors $K_p \leq 0.4$ (Table 4). The mean asymmetry factor does not exceed a value of 5.0%, which is, however, higher than the desired value of 1.0%. The Spearman conditioner provides the highest profile factors for the short separation distance. This corresponds to a more peaky profile compared to the Zanker and the tube bundle conditioners. However, the desired range of $0.8 < K_p < 1.3$ is not reached. With increasing distance all three conditioners exhibit similar profile factors outside of the admissible values.

Table 4: Asymmetry factors K_a and K_p at different distances downstream from the inlet using various flow conditioners.

z_{CSt}	$5D$		$110D$	
	K_a (%)	K_p (-)	K_a (%)	K_p (-)
Spearman	6.05	6.17	0.60	0.45
Zanker	6.63	6.91	0.45	0.39
Tube bundle	4.56	4.94	0.37	0.39

In conclusion, the conditioners have only a weak influence on the stratification, which is in agreement with the available data from the literature (Table 1). The profile remains flat and asymmetric, where the tube bundle provides the flattest.

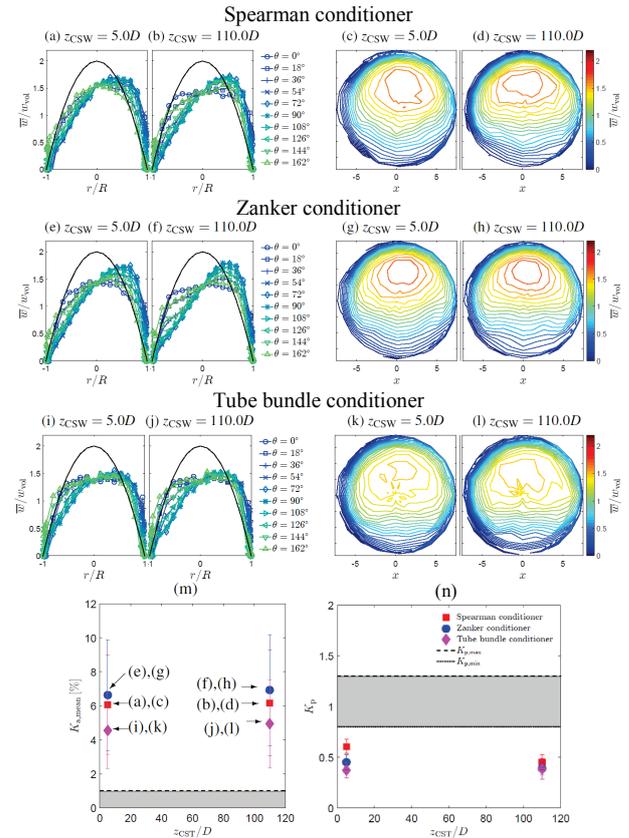


Figure 6: Contour plots and individual profiles of the axial velocity (a)–(l) along with comparison of K_a (m) and K_p (n) at two distances downstream from the inlet.

In the present experimental setup, the velocity profile is measured $12D$ downstream from the conditioner. Hence, a redevelopment of the stratification downstream from the conditioner is possible. Since the tube bundle

conditioner provides a very flat but less stratified profile, it performs best for conditioning stratified flow.

4. Summary and conclusions

All conditioners show good performance for the conditioning of swirling flow. While the Zanker conditioner performs best for decreasing the swirl angle and reaches values around the maximally admissible value of 2° , the Spearman as well as the tube bundle conditioner provide higher values. The Spearman conditioner shows high secondary velocities close to the wall. A comparison of the turbulence factor K_{Tu} shows that all tested flow conditioners lie within the desired range and, hence, provide reasonable turbulence intensities. The bundle conditioner provides the lowest K_{Tu} values and provides the best performance regarding the turbulence intensity.

For the conditioning of stratified flow, all flow conditioners provide unfavorable results. Both the profile and the asymmetry factor are outside of the admissible range. The profiles are still flat and exhibit strong asymmetries. Hence, none of the considered flow conditioners is efficient for conditioning stratification effects in laminar flow

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