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Experimentelle Untersuchung des laminar-turbulenten Umschlags in spiralförmig gewickelten Reaktoren mit LDA

Experimental investigation of the laminar-turbulent transition in helically coiled reactors with LDA

Conrad Müller*, Péter Kováts, Katharina Zähringer
Lehrstuhl für Strömungsmechanik und Strömungstechnik, Otto-von-Guericke-Universität Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany, *conrad.mueller@ovgu.de

Helixreaktor, LDA, PIV, Umschlagpunkt, Turbulenz
Helically coiled reactor, LDA, PIV, transition, turbulence

Zusammenfassung

Wendelrohrreaktoren (HCR) erfreuen sich zurzeit in der Verfahrenstechnik zunehmender Beliebtheit, da sie im Vergleich zu geraden Rohrreaktoren kleiner sind und einen besseren Wärme- und Stoffübergang bieten. Dies führt auch zu einem wachsenden Interesse an der Optimierung der Strömungsbedingungen in solchen Reaktoren. Der laminar-turbulente Übergang ist ein wichtiger Entwurfsparameter für die Leistung und Auslegung von HCRs. Die Literaturkorrelationen für die kritische Reynoldszahl in Abhängigkeit von den geometrischen Parametern der Wendel zeigen derzeit sehr heterogene Vorhersagen. Um diese Diskrepanzen zu verstehen und die Zuverlässigkeit der Übergangskorrelationen zu erhöhen, wird ein neuer Versuchsaufbau vorgestellt, der darauf abzielt, zusätzliche Einflüsse durch den Aufbau selbst so weit wie möglich zu eliminieren. Erste Geschwindigkeitsmessungen in einem Reynoldszahlbereich von $Re = 380$ bis $Re = 11700$ wurden mittels Particle Image Velocimetry (PIV) und Laser-Doppler-Anemometrie (LDA) durchgeführt und eine vorläufige Analyse wird im Folgenden vorgestellt. Sie zeigt die lokale Abhängigkeit des Turbulenzbeginns im Wendelquerschnitt und die Verbreiterung der Geschwindigkeitsverteilung mit zunehmendem Abstand vom Wendelbeginn. Auf der Grundlage dieser Ergebnisse werden in der Folge spezifischere Messungen mittels Hochgeschwindigkeits-PIV durchgeführt.

Abstract

Helically coiled reactors (HCRs) recently gained more popularity in process engineering, due to their smaller size and increased heat and mass transfer capabilities compared to straight tube reactors. This induces also an increasing interest for optimization of the flow conditions in such reactors. The laminar-turbulent transition is an important design parameter for the performance and layout of HCRs. Correlations for the critical Reynolds number in function of geometrical parameters of the coil present, at the time being, very heterogeneous predictions. In order to understand these discrepancies and increase the reliability of the transition point correlations, a new experimental setup is presented, which aims to eliminate as much as possible any additional influences from the set-up itself. First velocity measurements in a Reynolds number range from $Re = 380$ to $Re = 11700$ have been executed by Particle Image Velocimetry (PIV) and Laser-Doppler-Anemometry (LDA), and a preliminary analysis is presented in

the following. They show the local dependency of turbulence onset in the coil and the broadening of the velocity distribution with increasing coil number. Based on those results, more specific measurements will now be executed by high-speed PIV.

Introduction

Helically coiled tubes, also known as helical coiled reactors (HCRs), are commonly used in the fields of process engineering and biochemistry, especially in micro-reactors, to enhance heat and mass transfer. Their excellent radial mixing without axial backmixing, makes them a popular choice for homogenisation of momentum, temperature and concentration fields. With recent inventions in the field of coiled flows, like the coiled flow inverter (CFI) and the coiled flow reverser (CFR), the interest for a better understanding of flow patterns in coiled flow reactors increased. At moderate Reynolds numbers, flows in helical reactors form the characteristic Dean vortices, which are steady laminar vortices. With increasing flow velocities, more complex vortex structures can be found, which, however, show a strong dependency on the geometry and setup. These structures can be divided into the primary Dean vortices, secondary Lyne vortices, as well as temporary vortex structures (Müller et al. 2022). The transition from a laminar flow to full turbulence is one of various factors for the determination of the HCRs performance.

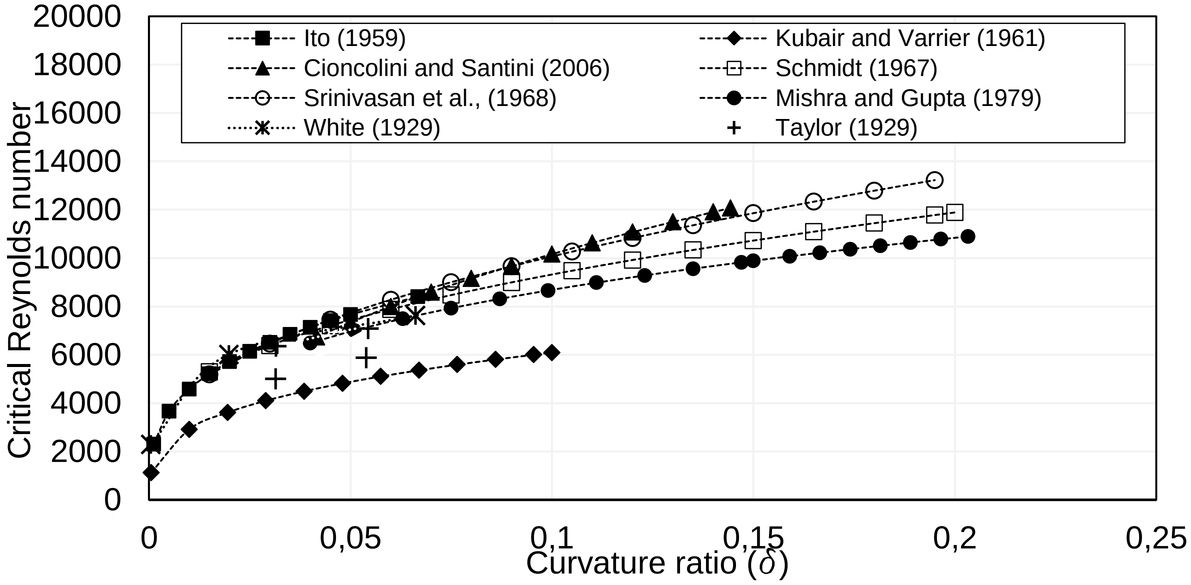

Fig. 1: Correlations of the critical Reynolds number for the laminar-turbulent transition in helically coiled tubes from different experiments in literature.

The first investigations concerning transition in coiled tubes were already carried out by Taylor or White in 1929. Until today, there have been several experimental and numerical attempts to describe transition by determining a critical Reynolds number as a function of the curvature ration $\boldsymbol{\delta} = \frac{\boldsymbol{d}}{\boldsymbol{D}}$, relating the tube diameter *d* to the coil diameter *D*. Several of those correlations are shown in Fig. 1. Although it seems obvious, that the critical Reynolds number is shifted to higher values compared to straight tubes **($\boldsymbol{\delta \rightarrow 0}$),** due to a re-laminarisation process, the results and correlation attempts drift widely apart. For example, a curvature ratio of $\delta = 0.1$ has a predicted critical Reynolds number in a range of $Re_{crit} = 6000 \ldots 10500$, depending on the correlation function used.

The reason may be found in different experimental and numerical set-ups and here especially the inflow conditions. The smallest changes in the geometry and setup of the reactors can

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induce strong changes in the vortex occurrence. Therefore, we propose here a new experimental setup aiming for an independency of the transition point to full turbulence from the flow history upstream and downstream the measurements section, by using a very long coil and excluding the coils near the inlet and outlet from the analysis. In fact, these coils serve as a re-laminarisation zone for the arriving and leaving flow and thus protect the measurement zone from external influences. From the first results it is shown that velocity fluctuations behave differently at different points of the cross-section in the helix. There are less fluctuations near the inner side of the cross-section, while the fluctuations near the outer wall of the coil are very strong, due to the formation of secondary vortices. Besides those geometrical differences, the definition of the onset of turbulence differs between the first appearance of velocity fluctuations for some correlations or the full development of random fluctuations for others. Therefore, Sreenivasan (1983) has introduced a transition area, instead of a fixed transition point. It includes the first appearance of velocity fluctuations in the flow up to the conditions at which the whole flow is fluctuating and full turbulence is developed.

In previous experiments the radial velocity flow field in HCRs was measured using PIV and the results are analysed here in the light of laminar-turbulent transition. These flow fields show different magnitudes of fluctuations for different regions inside one cross-section of the coil. This implies that turbulence occurs earlier at the outer side of the coil’s cross-section, further away from the coil’s core. The results of our first LDA measurements shown here for different Reynolds numbers confirm an influence of the inlet and outlet condition. Also the broadening of the velocity distributions with increasing coil number is shown and the geometrical measurement range for more specific further measurements by high-speed PIV is determined.

Experimental Setup

The measurements are carried out in a straight helix with 56 turns with an inner tube diameter of d_i = 10 mm, a core diameter of D = 118 mm and a coil pitch of p = 16 mm (Fig. 2, top left). It is made from FEP-tube with a refractive index of n = 1.3405. Reynolds numbers from 300 up to 12,000 are realized in the gravity driven setup with a 2 m^3 tank on 12 m height and controlled manually by a needle valve in the outlet and measured by an ultrasonic flowmeter in the inlet as shown in the flow chart in Fig. 2. The inlet and outlet to the HCR consists of 1 metre straight tubes. Between the ultrasonic flow meter and the needle valve, both, straight inlet and outlet, and the HCR were made from a single piece of tubing to avoid joints and thus edges.

Since the turbulent transition in a straight tube occurs at a critical Reynolds number of Re = 2300, at corresponding flow rates the flow enters the HCR with turbulent conditions. Inside the HCR the flow is re-laminarised and the transition shifted to higher Reynolds numbers. To ensure that the inlet and outlet have no influence on the transition point measured inside the helix, the number of turns necessary for this re-laminarization from the inlet or outlet is determined in the following using LDA. In that way, the flow conditions are stabilized before entering the measurement section and fluctuations induced by bending and rearranging the flow in the tubes and fittings of the inlet and outlet tubes are damped in the turns before or after.

The reactor itself is placed in an aquarium made of acrylic glass and filled with a refractive index matching 5.25$\%_{vol}$. glycerine-water solution, reducing refraction at the curved tube walls. This solution is also used as working liquid inside the tube. A 2D LDA system from Dantec is mounted on a 3D-traversing system to carry out measurements in different coils in the first half of the reactor. The main axial velocity component is measured in the centre of each coil and as a reference in the straight inlet (red crosses in Fig. 2 top left).

Calculating the critical Reynolds number from the correlations given in Fig. 1 and using the parameters of our reactor geometry, the range for the critical Reynolds number expands between $Re_{crit} = 5770 \dots 9440$ as shown in Table 1.

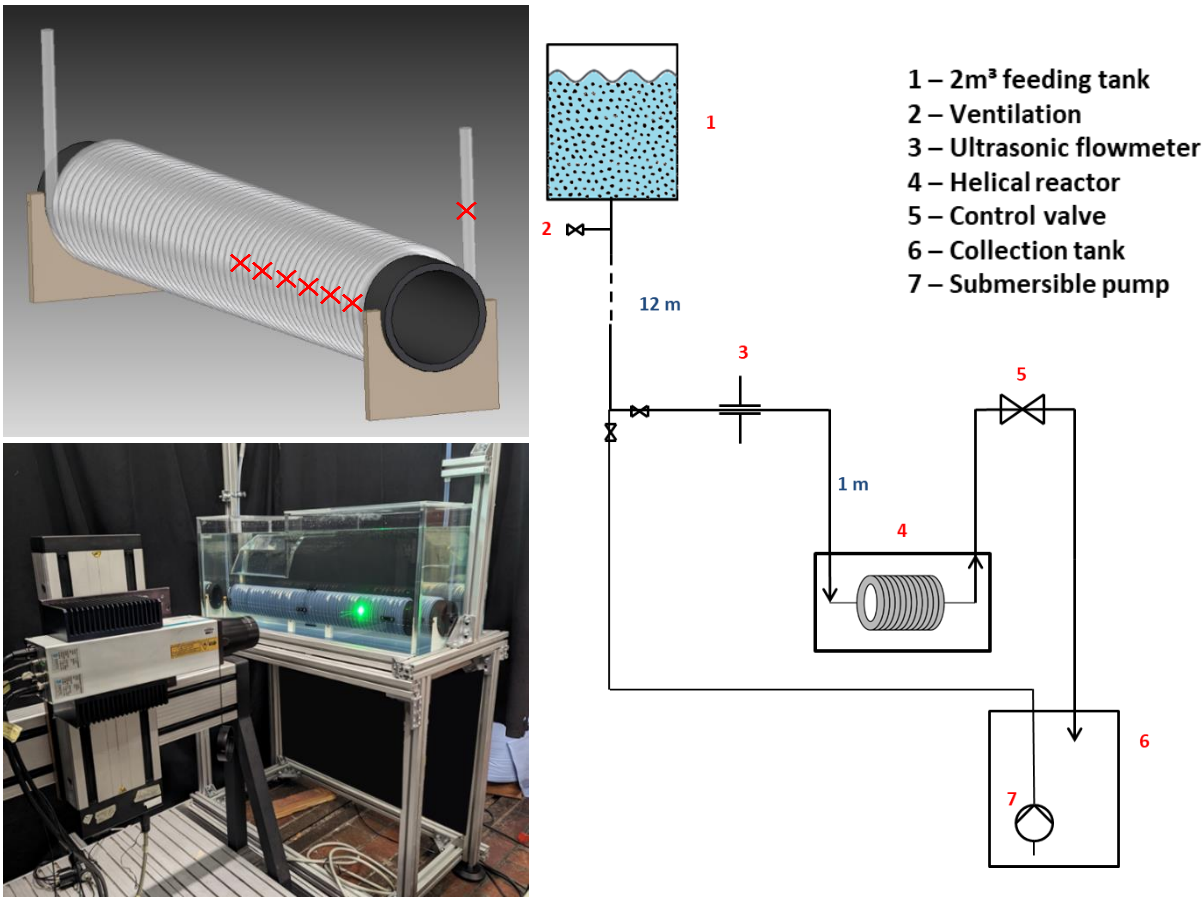

Fig. 2: Experimental Setup: CAD model of the HCR (top left), LDA setup and reactor in aquarium with refractive index matching solution (bottom left), flow chart (right).

Table 1: Correlations for the critical Reynolds number from Fig. 1 with geometrical parameters of the used experimental setup.

Source	**Re,crit.**	**Correlation formula**
Mishra and Gupta (1979)	8837	$Re_{crit} = 20000 \cdot \left(\delta\left(1+\frac{P}{\pi D}\right)^{-2}\right)^{0.32}$
Schmidt (1967)	8814	$Re_{crit} = 2300 \cdot (1 + 8.6 \cdot \delta^{0.45})$
Srinivasan (1968)	**9436**	$Re_{crit} = 2100 \cdot (1 + 12 \cdot \delta^{0.5})$
Cioncolini and Santini (2006)	9405	$Re_{crit} = 30000 \cdot \delta^{0.47}$
Kubair and Varrier (1961)	**5779**	$Re_{crit} = 12730 \cdot \delta^{0.32}$

PIV Results

In previous works of the authors (Müller 2021, 2022 and Kováts 2018, 2020 a and b) various vortical structures have been identified at different positions in the cross-section of a helical coil. In a first attempt to analyse these previous results in the light of laminar-turbulent transition, the velocity magnitudes of the flow fields in the top cross-section of a HCR were examined. Small areas at different positions inside that cross-section (Fig. 3, yellow squares) were selected and the spatial mean velocity in those areas was plotted over time in Fig. 4 for different Reynolds numbers.

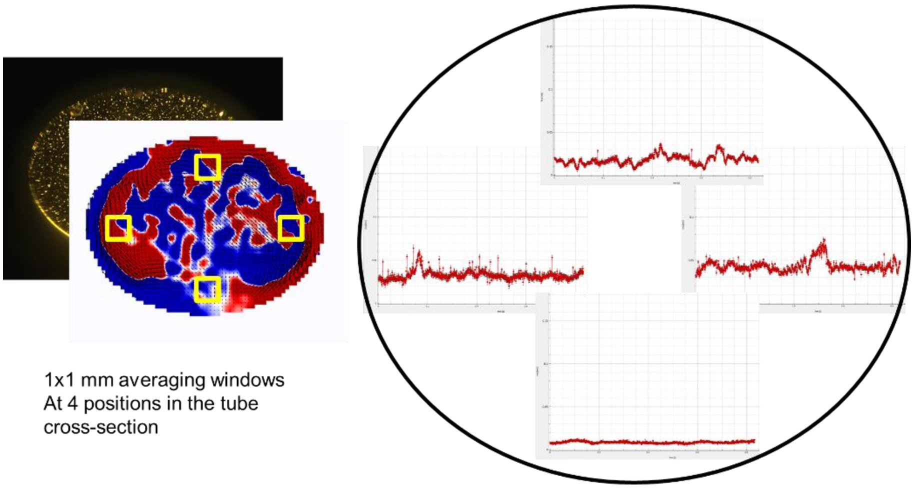

Fig. 3: Processing of previous PIV results. Spatial velocity averaged over the yellow areas (left) is plotted over time for 4 different positions in the velocity field cross-section (right).

Obviously, with increasing Reynolds number, the velocity magnitude increases and so do the temporal velocity fluctuations. However, it becomes clear from these four figures, that the velocity differs strongly for the different locations in the cross-section. The highest velocities are determined on the left and right side, whereas the velocity at the bottom (Fig. 4, bottom right), closer to the core of the HCR, is very small.

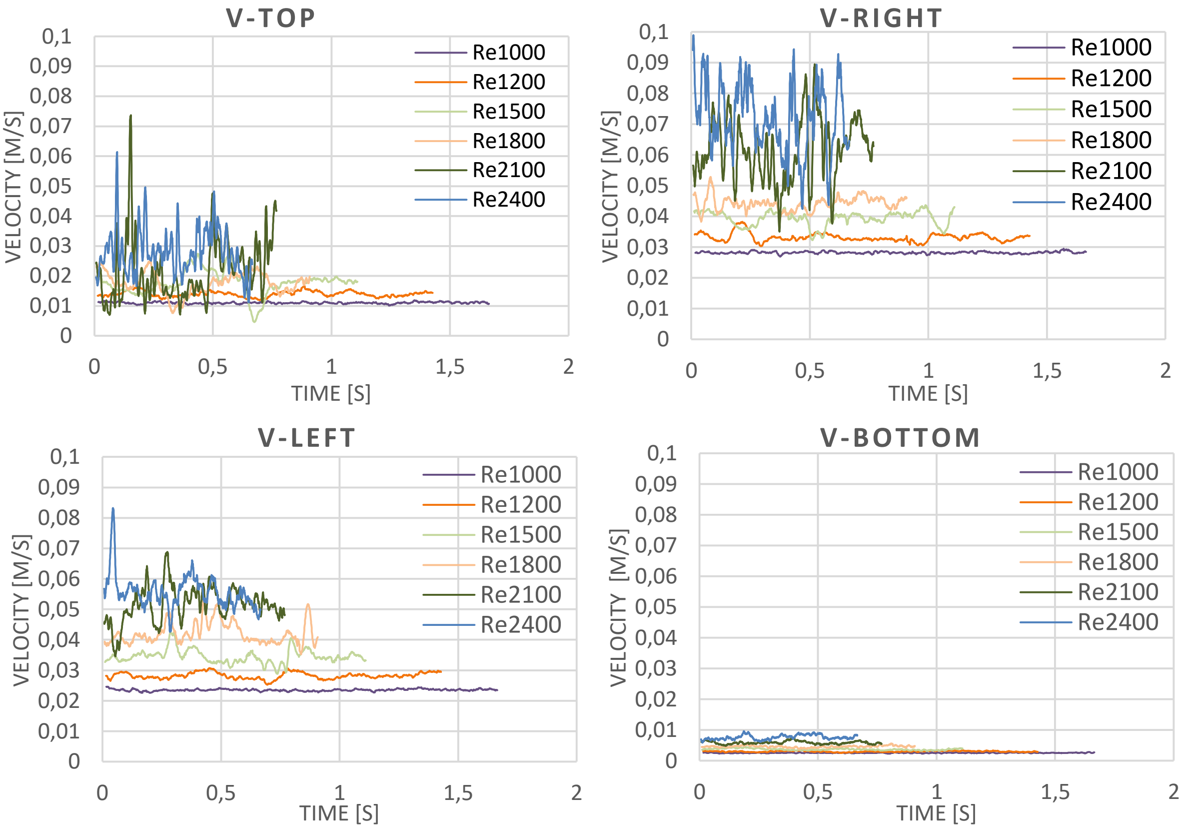

Fig. 4: Velocity profiles over time at four different positions in the cross-sections of the HCR for different Reynolds numbers.

If one investigated the degree of turbulence for those different positions, it would occur that turbulent behaviour appears at lower Reynolds numbers in the top as it would at the bottom of the cross-section. The earliest transition would be found on the two sides. This leads to the conclusion, that for the turbulent transition in coiled tubes a critical Reynolds number dependency exists on the location in the cross-section itself and at the inner side of the coil (here bottom of the cross-section) a re-laminarisation can occur as predicted by Kurokawa et al. (1998).

LDA Results

It is well known, that HCRs have a re-laminarising effect on the flow. However, it is unclear after how many coils a full re-laminarisation has taken place. Therefore, LDA measurements of the axial main velocity component in the centre of each coil have been executed to determine the number of coils necessary for an inlet-independent flow field in the coil. The following Fig. 5 shows exemplary the histograms for the highest Reynolds numbers of the measured range between Re = 380…11,700, covering the range of critical Reynolds numbers at which the laminar-turbulent transition is forecasted by the literature correlations (Table 1).
For the highest measured Reynolds number of Re = 11,700 (Fig. 5) the velocity distribution for the inlet peaks at 1.47 m/s, shifting to higher velocities in the first coils. After further coils the velocity distributions are widened and the peak is displaced to slower velocities. Between the 14th and 26th coil the velocity distribution does not change any more, corresponding to an independency of the inlet conditions.
This trend is the same for lower Reynolds numbers, where the velocity peak first shifts to higher values directly after the inlet and then leans to slower but wider velocity distributions.

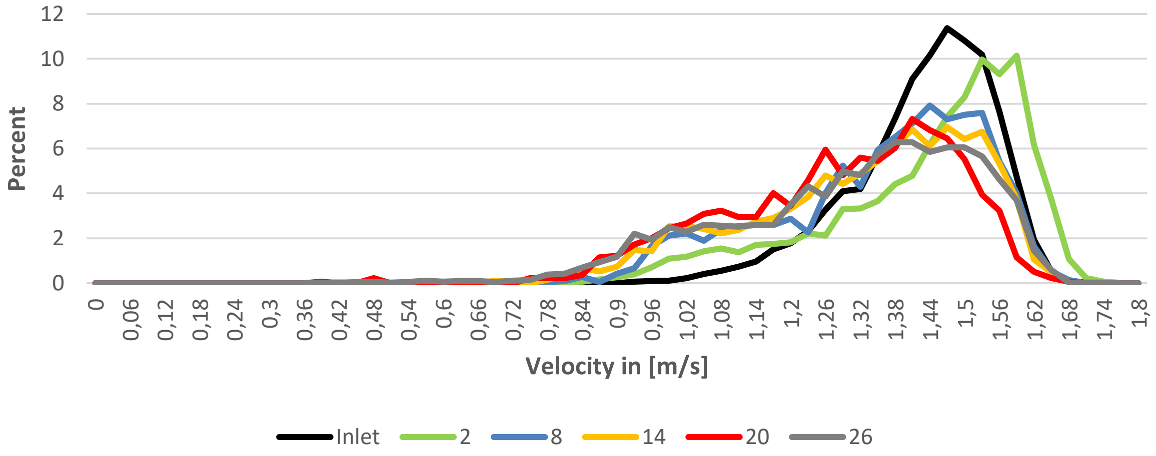

Fig. 5: Velocity distributions over coil numbers after the inlet of the HCR for the highest measured Reynolds number Re = 11700 with a volume flow of Q = 5.52 L/min

For a more precise investigation, the standard deviation of the velocity is plotted in Fig. 6 as StdDev (top) over the Reynolds number and coil number and as StdDev normalized by the average velocity (bottom). While in the laminar case the standard deviation in the inlet is the same as in all following coils, the standard deviation at increasing Reynolds number increases with the number of coils from the inlet. In the graph at the top right, one would expect a plateau after a certain number of coils, indicating stable flow conditions. This seems to be reached for the lower Reynolds numbers after about 15 coils, but increases with the Reynolds number to about 25 coils for Re = 8000. The normalized fluctuations (bottom left) are larger for smaller Reynolds numbers than for high Reynolds numbers, where they form a plateau, that is even lower than in the laminar case. The normalized standard deviation also varies more with increasing coil number for lower Reynolds numbers than for the higher ones (bottom right).

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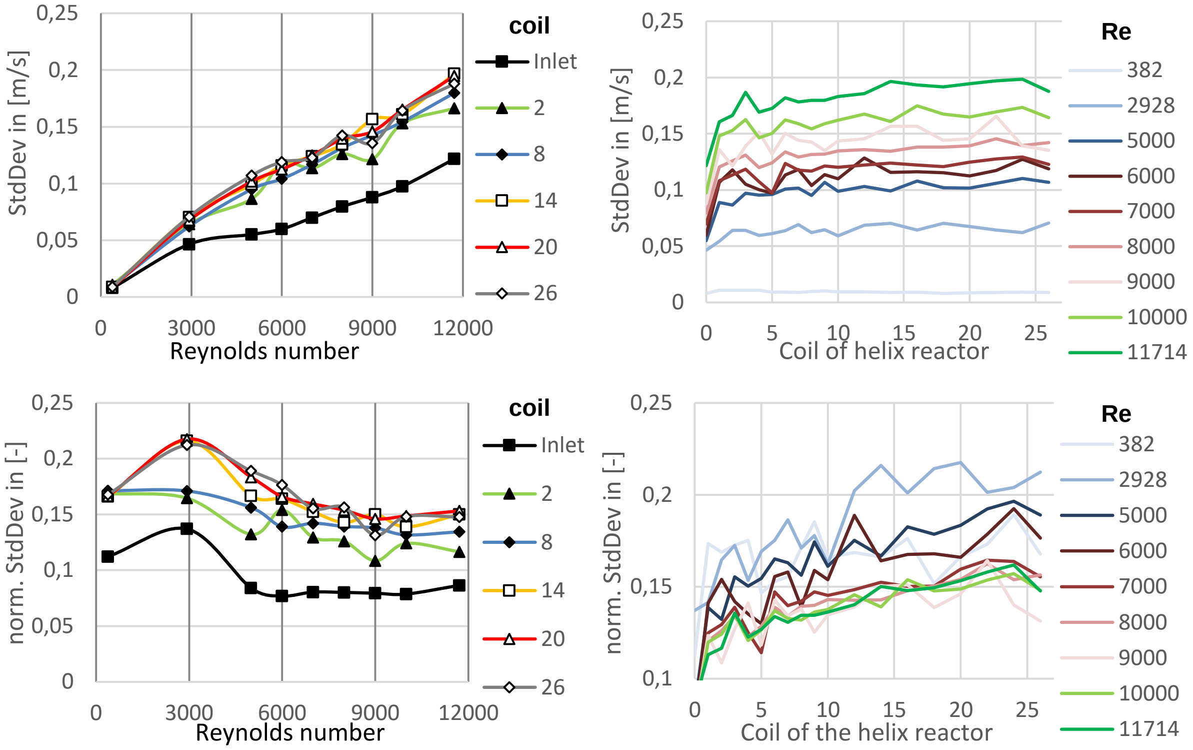

Fig. 6: Standard deviation (top left) and normalized standard deviation (bottom left) over Reynolds number for different coils (left), standard deviation (top right) and normalized standard deviation (bottom right) over number of coils for different Reynolds numbers

Conclusions and outlook

The first results presented here and concerning the influence of the reactor geometry and the Reynolds number on the laminar turbulent transition in helically coiled reactors can be concluded as follows:

- Geometric independency from the inlet and outlet can be achieved after approximately 25 coils for Reynolds numbers up to Re = 12,000.

- A clear transition point between laminar and turbulent behaviour has to respect and differentiate between time-resolved full turbulence and turbulent puffs, as well as between spatial differences where turbulence appears in outer parts of the tube cross-section earlier than in inner parts of the same cross-section.

In the following, additional LDA measurements will be performed, regarding the main velocity component at five different positions in the cross-section. Histograms of the velocity distributions indicate the geometric independency from the inlet and outlet. The LDA signal will be further analysed with NFFT (Non-equidistant fast Fourier transformation) to quantify appearing frequencies. In a next step, high-speed PIV measurements will be processed using the spectral entropy method, resulting in a single scalar value indicating turbulent ($E_S > 1$) or non-turbulent ($E_S < 1$) behaviour. Further, 3D velocity measurements are planned using the shake-the-box algorithm to analyse all 3 velocity components at once.
The results will then be used to validate CFD simulations. Additionally, the inner diameter of the coiled tubes will be varied to cover a broader range of curvature ratios as well as modern coiled flow geometries like the coiled flow inverter and coiled flow reverser. This will lead to the main goal of this project, by creating a detailed map for the transition from laminar to turbulent flow in helical coils with respect to partial and full turbulence.

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