The effect of Reynolds number on near-wall reverse flow in a turbulent duct flow

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Abstract. The influence of the Reynolds number on the statistics of a near-wall reverse flow phenomenon, taking place in a turbulent duct flow, is studied. An increase in the NWRF probability is found in both the core and corner regions of the duct walls for higher Reynolds number. The mechanism of the NWRF formation, described recently by Zaripov et al. [1, 2], is validated for higher Reynolds number flows.

1. Introduction
The existence of a near-wall reverse flow (NWRF) phenomenon was of great discussion for a long time. A lot of experimental and numerical evidence was found in recent years. However, their nature is turned to be different under different flow conditions. For instance, several possible theories of its generation were found for channel and pipe flows [3], adverse pressure gradient flow [4], and duct flow [1]. In the latter case, two different mechanisms of the NWRF generation were discovered in the core and corner regions of the duct walls [2], when considering the turbulent flow at a relatively low Reynolds number Re = UbH/ν = 3150, with Ub, H, and ν representing the bulk velocity, half-width of the channel, and kinematic viscosity, respectively. As it turned out, the NWRF events appearing in the corner region of the duct have a probability of their occurrence three orders of magnitude higher than the events appearing in the core region of the wall.

According to Guerrero et al. [5], Lenaers et al. [6], and Hu et al. [7], who studied the NWRF phenomenon in the pipe and channel flows, the probability of their occurrence increases with an increase in the Reynolds number. Therefore, it is expected that the events appearing in the duct corners should also increase. Thus, in the present study, firstly, we aim to figure out the existence of the NWRF phenomenon in the duct corners at a higher Reynolds number and, secondly, to verify the mechanism of their formation if it exists.

2. Results
The turbulent duct flow at Reynolds number Re = 6300 (Reτ = 378) is studied by direct numerical simulation using spectral computational code Nek5000 [8] that solves the discretized Navier-Stokes equations. The spatiotemporal discretization used in the present research was the same as in [1, 2] used for a lower Reynolds number flow. As it is shown in [2], the chosen discretization degree allowed for the simulation at a higher Reynolds number. The total number of grid points exceeded 100 million. The data were collected during the time period TUb/H = 10, corresponding to T = 227 in wall units. Figure 1 shows the distribution of the local wall-shear stress (WSS), normalized by the perimeter-averaged WSS. Good agreement with the data of Vinuesa et al. [9] and Zaripov et al. [2] can be seen.
The distribution of the local WSS, normalized to its perimeter-averaged value, in the cross-flow direction in comparison with the literature data [2, 9].

The distribution of the NWRF probability along the cross-flow direction is demonstrated in figure 2. An increase in the NWRF probability with an increase in the Reynolds number is observed in the core region of the wall (0 < z/H < 0.8). This is consistent with the general trend observed by Hu et al. [7] and Vinuesa et al. [9] for channel flow. For the corner region of the duct wall (z/H = 1), the NWRF probability increases from 12.5% for Reτ = 204 to 15.6% for Reτ = 378. Such behavior suggests a faster achievement of Reynolds number invariance for the NWRF events appearing in the corner region of the duct. The decrease in the NWRF probability at z/H = 0.9 is clearly seen in figure 2, despite the data scarcity problem. This wall region, characterized by a reduced NWRF probability, is located slightly closer to the duct corner as compared to the same region (z/H ≈ 0.8) for a lower Reynolds number, which can be explained by a different WSS distribution in the vicinity of the duct corner (0.8 < z/H < 1), seen in figure 1. Nevertheless, a decrease in the NWRF probability suggests the presence of two different mechanisms of the NWRF formation for the core and corner regions of the duct, as it was shown in [2].

Figure 1. The distribution of the local WSS, normalized to its perimeter-averaged value, in the cross-flow direction in comparison with the literature data [2, 9].

Figure 2. The distribution of the NWRF probability in the cross-flow direction in comparison with literature data [2, 6].
The NWRF regions were detected and tracked according to approaches described in [1, 2] in detail. The histograms of a lifetime of the NWRF events, which appear in the core and corner regions for two Reynolds numbers, are compared in figure 3. It should be noted that the data, obtained for a lower Reynolds number flow case ($Re_\tau = 204$, [2]), were collected during a time period $T^+ = 3308$, which is about 14.5 times longer than in the considered flow case ($Re_\tau = 378$). Therefore, for the purpose of comparative analysis, the number of tracks presented in figure 3 for $Re_\tau = 378$ was pre-multiplied by a factor of 14.5.

Interestingly, during the simulation, 141 independent tracks were detected in the core regions of all four duct walls ($0 < z/H < 0.8$) and 247 tracks were detected in all four corner regions ($0.8 < z/H < 1.0$). While the number of independent tracks detected in these wall regions differs significantly for $Re_\tau = 204$, i.e. 197 events detected in the core region vs. 1308 events detected in the corner region. The change in their mean lifetimes is also different: $T^+ = 6$ and 17 for the events appearing in the core and corner regions at $Re_\tau = 204$, respectively, vs. $T^+ = 9$ and 19 for the same events observed at $Re_\tau = 378$.

![Figure 3](image.png)

**Figure 3.** The histograms of a lifetime of the NWRF events occurring in the core and corner wall regions.

3. **Conclusion**

The NWRF phenomenon was studied by direct numerical simulation of the turbulent duct flow at $Re_\tau = 378$, complementing the results presented in [2] for a lower Reynolds number. As expected, an increase in the NWRF occurrence probability with an increase in the Reynolds number in both the core and corner regions was found. However, this increase in the probability is found to be slower for the events occurring in the corner region. The same trend is applied to the number of the NWRF tracks and their lifetimes, i.e., while 1308 (197) events with a mean lifetime of 17 (6) in wall units were detected in the corner (core) wall region at $Re_\tau = 204$, 247 (141) events with a mean lifetime of 19 (9) were detected at $Re_\tau = 378$. Nevertheless, the same shape of the distribution of the considered quantities suggests the preservation of the mechanism of the NWRF formation in both core and corner duct regions when increasing Reynolds number.

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