RESPONSES OF LOW- AND HIGH-SPEED STREAKS TO INJECTION OR SUCTION IN A MINIMAL FLOW UNIT

Hideo Yoshida
Department of Mechanical Engineering, Kyoto University
Sakyo-ku, Kyoto 606-8501, Japan

Kenichi P. Kobayashi
Department of Mechanical Engineering, Meiji University
Tama-ku, Kawasaki 214-8571, Japan

Sigeru Tada, Kazuhiro Higuchi, Takashi Nozaki
Department of Mechanical Engineering, Tokyo Institute of Technology
Meguro-ku, Tokyo 152-8552, Japan

Ryozo Echigo
Department of Mechanical Engineering, Shibaura Institute of Technology
Minato-ku, Tokyo 108-8548, Japan

ABSTRACT

Direct numerical simulations with external perturbations have been performed in order to clarify the dynamics of the turbulent coherent structure near a wall, and also the possibility of active control of turbulence. To extract the elementary processes of turbulence, the domain of the numerical calculation is a minimal flow unit with a Reynolds number of 1730. A series of flow injections or suctions with Gaussian distribution are administered on both the lower and upper wall surfaces so that they interact with the coherent structure, especially, the high- and low-speed streaks along the flow direction. The various responses of the streaks to the injection or suction are systematically examined. The observed transient behavior, for example, growth or decay of the coherent structures, affords fundamental knowledge for turbulence control in the future.

INTRODUCTION

In order to clarify the principal mechanism of wall turbulence, and to examine the possibility of turbulence control in the future, it is crucial to investigate the responses of turbulence structures to external perturbations. Among the many kinds of external perturbations, injection and suction at the wall are considered to be the most easily applicable for actual flow control.

From this viewpoint, the authors have been interested in the responses of coherent structures to local injection or suction, of a lengthscale of the same order of magnitude as that of the coherent structures. In an experiment using the endless Couette flow within a concentric annulus, the flow excitation by injection and suction through slits distributed on the wall was investigated (Yoshida et al., 1993); although turbulence amplification was confirmed at specific frequencies of perturbation, the methodology used in the experiment introduces some ambiguity as to whether the relatively intense external perturbation essentially alters the flow irrespective of the original turbulence structure.

On the other hand, numerous studies on turbulence control by wall actuation have been performed recently. Typical examples are the direct simulation by Carlson and Lumley (1996) and the experiment by Jacobson and Reynolds (1998).

Inspired by these studies, we conduct a direct simulation of wall turbulence with injection or suction. Since attention was focused on the pure responses of the coherent structure, the minimal flow unit proposed by Jiménez and Moin (1991) is employed. To elucidate the effects of injection or suction below low- and high-speed streaks, the calculation is carried out systematically by varying the initial conditions.

NUMERICAL METHOD

Flow Geometry

As shown in Fig. 1, the test bed is a minimal flow unit with periodic boundary conditions in the streamwise and

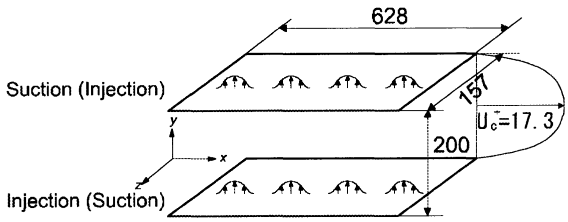


Figure 1. Schematic of the calculation domain

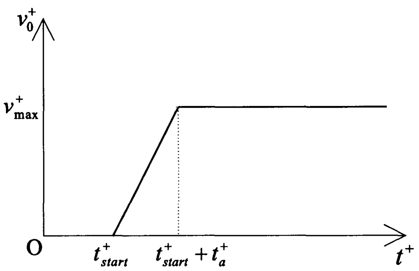


Figure 2. Variations with time of injection or suction velocity

spanwise directions. The length, height and width of the computational box are $x^+ = 628$, $y^+ = 200$ and $z^+ = 157$ wall units, respectively. (In this paper, the superscript + denotes wall units.) The Reynolds number Re_c, based on the centerline velocity U_c and the channel half-width δ, is set as 1730.

In the present study, attention is focused on the lower-half volume of the calculation domain. The injection or suction is administered through four locations on the lower wall; to maintain a constant flow rate, countersuction or -injection is administered at the upper wall. The normal velocity at the point of injection or suction is given by the Gaussian function

$$v_0^+ = \pm v_{0max}^+ \sum_{i=1}^{4} \exp\left\{-\frac{1}{\sigma^2}\left[\left(x^+ - x_i^+\right)^2 + \left(z^+ - z_0^+\right)^2\right]\right\} , (1)$$

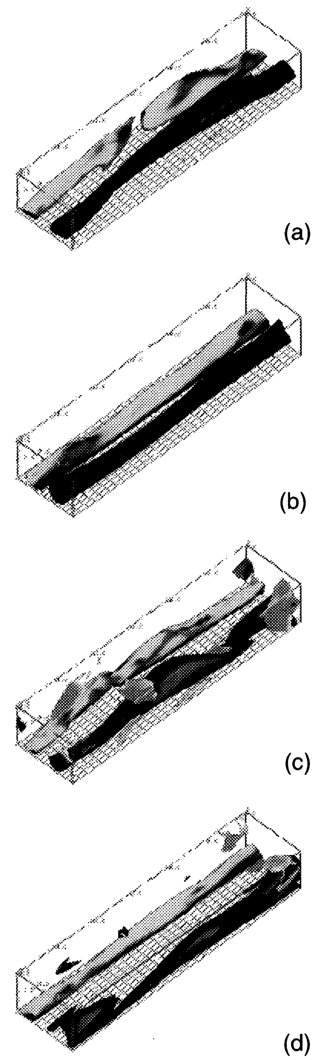
where $\sigma = 20$ and $v^+_{0max} = 0.5$, with $x_1 = 157$, $x_2 = 314$, $x_3 = 471$, and $x_4 = 628$. The injection or suction velocity v_0 is varied as shown in Fig. 2, where $t^+_{start} = 20$ and $t^+_a = 10$.

The investigated flow manipulations are classified into the following cases:

- Unactuated, i.e., natural state
- A: Injection below a low-speed streak
- B: Suction below a high-speed streak
- C: Injection below a high-speed streak
- D: Suction below a low-speed streak

Numerical Procedure

The numerical procedure used is basically the same as that developed by Kim et al. (1987). A spectral method is used with Fourier series in the x and z directions and a Chebyshev polynomial expansion in the y direction. The grid points are 32, 65 and 16, for the x, y and z directions, respectively.



(a) Condition 1

(b) Condition 1'

(c) Condition 2

(d) Condition 3

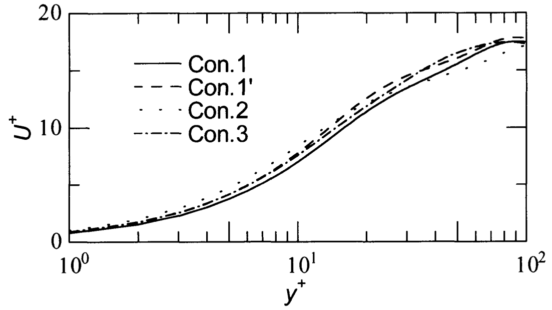
Figure 3. Flow structure at the initial state

(light): $u'^+ > 3.0$, (dark): $u'^+ < -3.0$

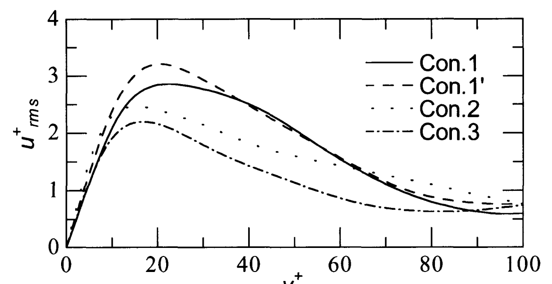
Initial Conditions

Since the purpose of the present study is to observe well-defined responses of turbulence, a simple flow structure before the manipulation is desired. To this end, from the numerous time steps in the simulations, we chose four typical initial conditions in which a pair of simple low- and high-speed streaks exists.

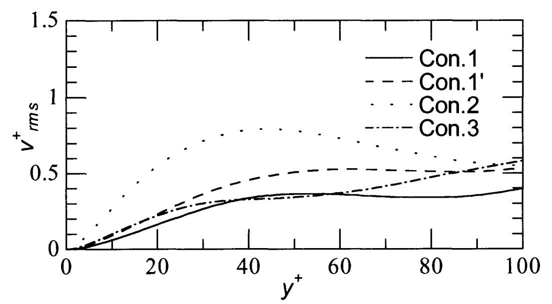
Figure 3 (a) - (d) shows the flow structures at the initial state thus chosen for the simulation. The streamwise velocity and the three components of the root-mean square velocity



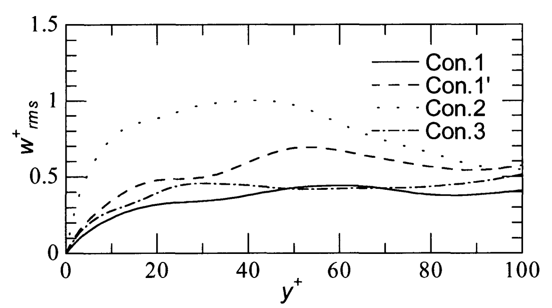
(a) Mean-velocity profile



(b) Root-mean-square velocity fluctuation in x direction



(c) Root-mean-square velocity fluctuation in y direction



(d) Root-mean-square velocity fluctuation in z direction

Figure 4. Velocity profiles averaged over the plane of y = constant at each initial state

TABLE 1. RESPONSE OF TURBULENCE

manipulation	Con. 1	Con. 2	Con. 3
A: Injection below low-speed streak	++	++	++
B: Suction below high-speed streak	+	0	0
C: Injection below high-speed streak	0	+	+
D: Suction below low-speed streak	-	-	0

fluctuation averaged over the plane of y = constant are shown in Figs. 4 (a) - (d).

Although the mean velocities are not significantly different from each other, large differences between the velocity fluctuations are noted. For Conditions 1 and 1', the streamwise component is large, while the normal and spanwise components for Condition 2 are much larger than those of the other conditions. For Condition 3, all the fluctuating components are small.

In Figs. 5 (a) - (d) and 6 (a) - (d), the solid lines show the variations with time of the volume-averaged Reynolds shear stress and turbulence energy, respectively, for the unactuated case. As mentioned above, since each initial flow structure consists of a pair of simple streaks, the space-averaged Reynolds shear stress for the initial state is lower than the time-averaged value for a conventional channel flow, which is indicated by the horizontal dashed line at $-u^+v^+ = 0.34$ in Figs. 5 (a) - (d). On the other hand, in Figs. 6 (a) - (d), the volume-averaged turbulence energy k^+ at the initial state is not significantly different from the time-averaged value for a conventional channel flow, i.e., $k^+ = 1.6$.

Turbulence energy is considered to be the most specific quantity characterizing the turbulence field. Hence, we use it as the index for turbulence response. However, as the cause of the turbulence response, the main focus, in the present study, is the Reynolds shear stress. Thus, from Figs. 5 (a) - (d), we regard that for $0 < t^+ < 100$, the Reynolds shear stress is

- Condition 1: neutral,
- Condition 1': neutral,
- Condition 2: increasing,
- Condition 3: decreasing.

Consequently, for all the combinations of the five kinds of flow manipulations, including for the unactuated case and the four initial conditions, systematic calculations for a total of 20 cases were performed for a fixed Reynolds number.

As is evident from Figs. 5 - 6 , the results for the similar initial conditions, Condition 1 and Condition 1', are almost consistent with each other. Therefore, we expect that a comprehensive conclusion can be drawn from three kinds of

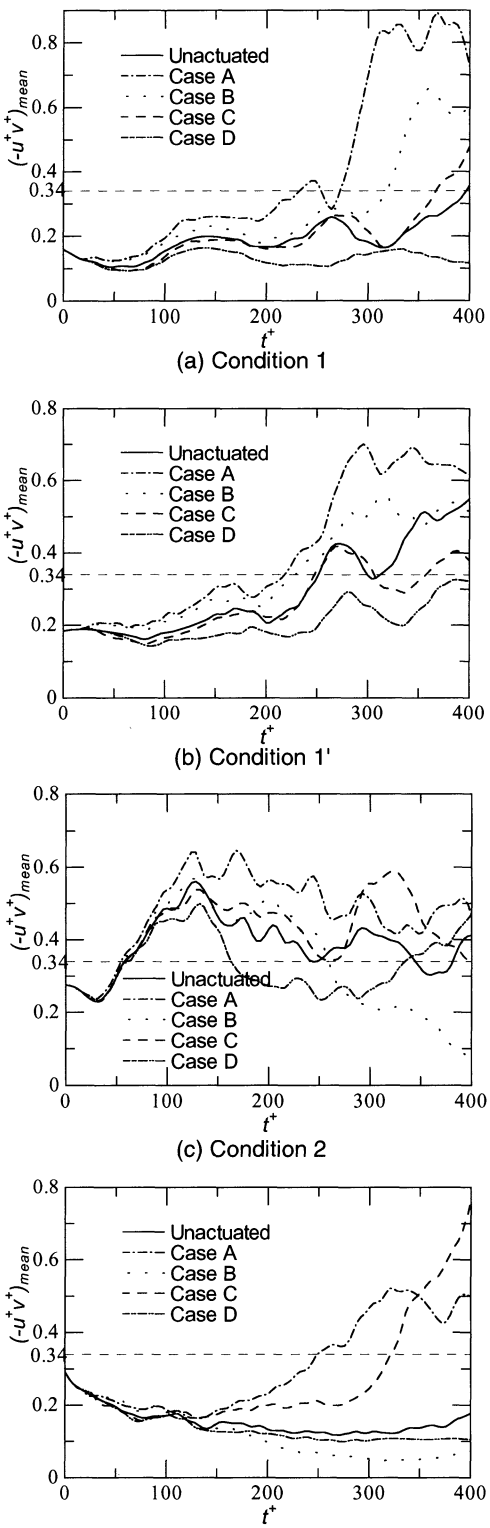


Figure 5. Variations with time of volume-averaged Reynolds shear stress

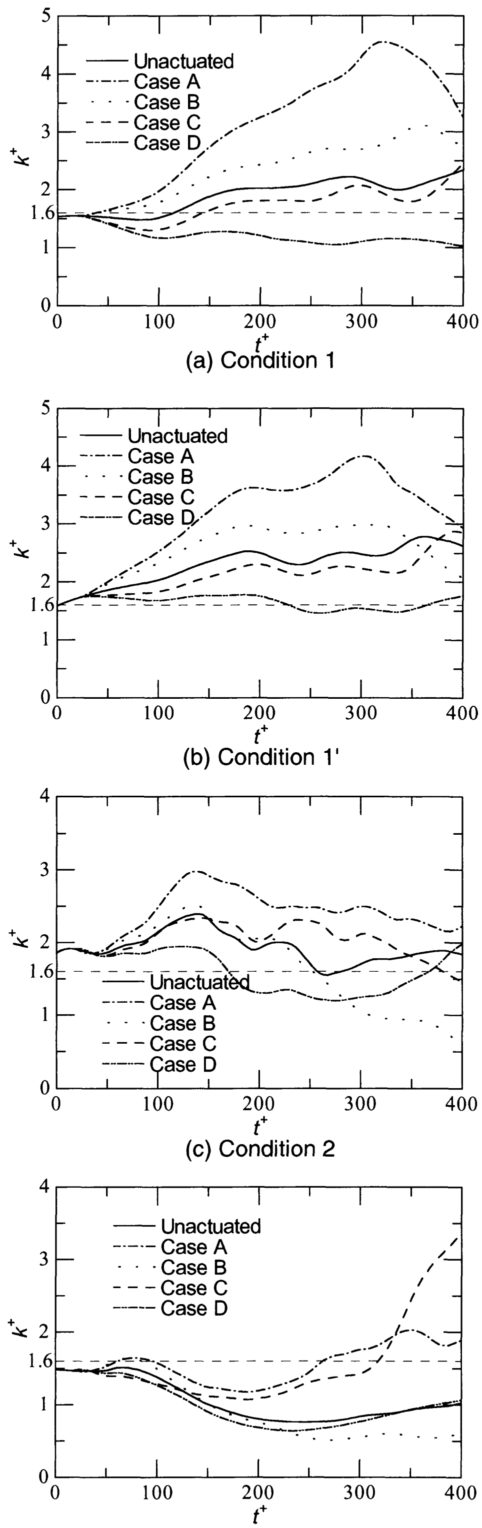


Figure 6. Variations with time of volume-averaged turbulence energy

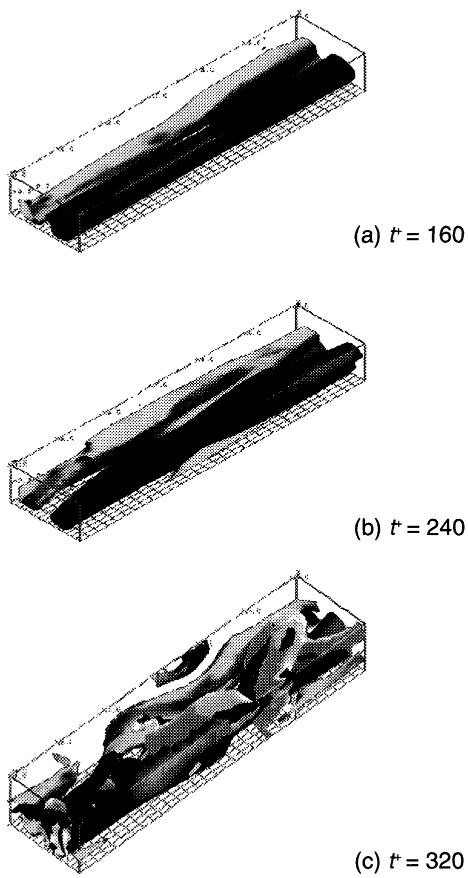


Figure 7. Injection below low-speed streak for Con. 1
: $u'^+ > 3.0$, : $u'^+ < -3.0$

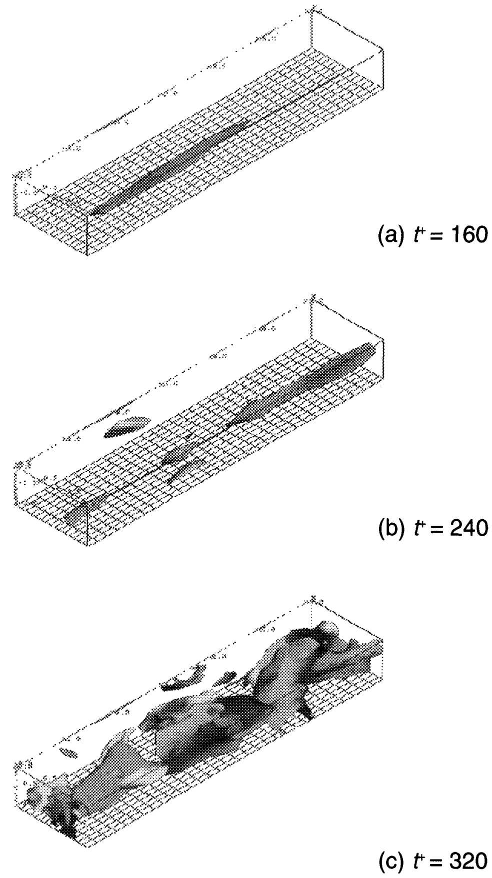


Figure 8. Injection below low-speed streak for Con. 1
: $p'^+ < -2.5$, : ejection, : sweep

initial conditions, i.e., neutral, increasing, and decreasing Reynolds shear stress.

RESULTS AND DISCUSSION

Figures 5 (a) - (d) and Fig. 6 (a) - (d) show the variations with time of the space-averaged Reynolds shear stress and turbulence energy, respectively, for the various flow manipulations. Tables 1 summarizes the turbulence responses for each of the initial conditions. These responses were judged on the basis of the total turbulence energy integrated for $0 < t^+ < 300$; the + (++) sign and the - sign denote increase and decrease compared with the unactuated case, while the 0 sign denotes no noticeable change.

From Tables 1, it can be seen that injection below a low-speed streak increases the turbulence level irrespective of the initial condition. The effect of the other three manipulations, however, is complex depending on the initial condition. Since it is difficult to include all the twelve responses in this paper, attention is focused on two typical responses which showed noticeable changes from the unactuated case.

Case A for Condition 1

In Case A (injection below a low-speed streak) for Condition 1, the turbulence energy gradually increases as shown in Fig. 6 (a), and a dramatic increase of Reynolds shear stress occurs for $t^+ > 250$, as seen in Fig. 5 (a). The development of the turbulence structure in this case is shown in Figs. 7 and 8. At $t^+ = 240$, just before the dramatic increase of Reynolds shear stress, there exists a narrow but long ejection region over the four injections, and simultaneously, a sweep region appears above the high-speed streak. At $t^+ = 320$, where the turbulence energy is maximal, a typical horseshoe-shaped low-pressure ejection region develops above the injection, and also a sweep region follows downstream of the ejection region; meandering of the streaks is also observed.

Case D for Condition 1

In Case D (suction below a low-speed streak) for condition 1, turbulence suppression occurs continuously, as seen from

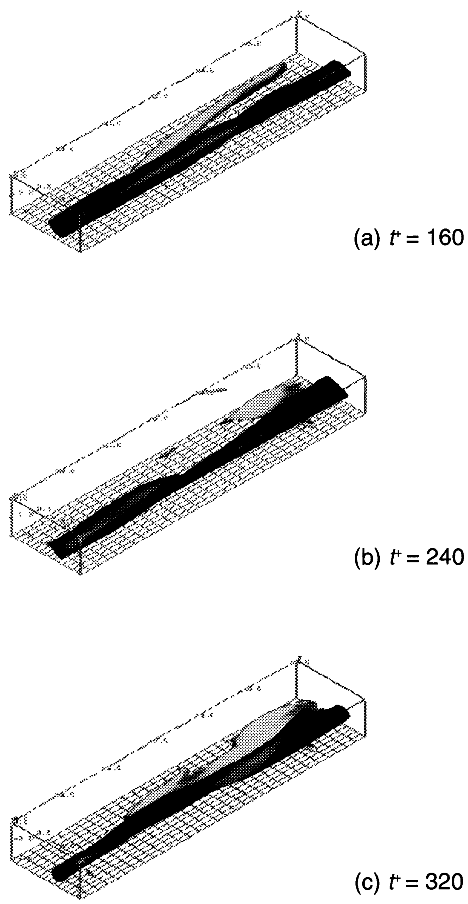


Figure 9. Suction below low-speed streak for Con. 1
: $u'^+ > 3.0$, : $u'^+ < -3.0$

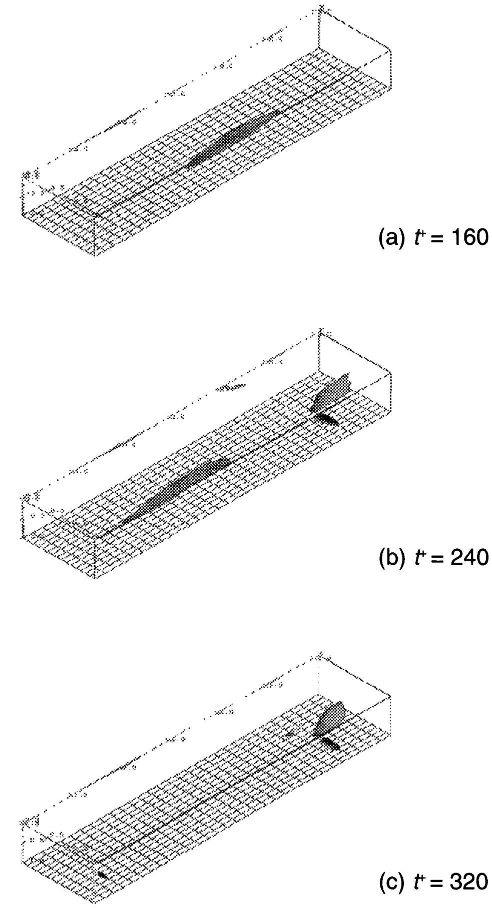


Figure 10. Suction below low-speed streak for Con. 1
: $p'^+ < -2.5$, : ejection, : sweep

Figs. 5 (a) and 6 (a), The decay of the turbulence structure in this case is shown in Figs. 9 and 10. Suction below a low-speed streak attenuates both the low- and high-speed streaks, which leads to laminartype of flow. This tendency is in striking contrast to that observed in the case of suction below a high-speed streak, (Case B for Condition 1).

CONCLUDING REMARKS

The responses of low- and high-speed streaks to injection or suction is studied by direct numerical simulation. The combination of a minimal flow unit and simple initial flow condition elucidates a relatively simple behavior of wall turbulence for various cases. At the present stage, however, the data analysis is limited. On the basis of the present data, more detailed examination on the turbulence mechanism is now in progress.

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