博士論文の内容の要旨
Abstract of Doctoral Dissertation

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The transition from laminar flow, which has no influential disturbance, to turbulent flow is a phenomenon of great engineering importance to describe and predict because the transition dramatically increases mixing and heat transfer. Not only that, it has also been attracting attention in science as a representative example of a chaotic process. In particular, the transitions of canonical flows such as boundary layer, circular pipe, Couette, and two-dimensional channel flows have been studied extensively by experiments, theories, and direct numerical simulations (DNS). Despite these studies, the understanding of transition phenomena is still limited, for example, prediction methods for boundary layer transitions have not been fully established.

One of the classical approaches to investigations of transitions is the linear stability theory, which determines whether a flow is unstable or not in response to an infinitesimal disturbance. By assuming that the disturbance is infinitesimal, the linear equation for the disturbance is derived from the Navier-Stokes equation, the temporal or spatial growth rate of the disturbance is determined, and the stability of the flow is determined by the positive or negative growth rate. Experiments have confirmed the linear growth of unstable modes based on linear stability theory for the generation of Görtler vortices in boundary layers on concave surfaces and Rayleigh–Bénard convection that occurs when the underside of a stationary fluid is heated. When the flow is inherently unstable as such flows, linear stability theory provides important clues for clarifying the transition, whereas the transition process in circular pipe flow has been an open problem for long time because the transition is stable against infinitesimal disturbances. Transitions such as circular pipe flow are called subcritical transitions because they occur at a Reynolds number lower than the critical Reynolds number at which infinitesimal disturbances begin to grow, and the transition process is essentially governed by nonlinear dynamics. As in research of turbulence, the difficulty in the mathematical treatment of nonlinear dynamics has hindered our understanding of subcritical transitions.

During the past two decades, however, theories of flow instabilities has been extended to include nonlinear behavior, and our understanding of circular pipe flow is rapidly improving. The transition in circular pipe flow requires that the initial disturbance be strong enough to cause nonlinear behavior of the flow, and above a certain Reynolds number, such a strong disturbance causes local turbulence in the circular pipe flow, such as puffs and slabs, and as the Reynolds number is increased, the flow becomes turbulent throughout the entire axial direction of the circular pipe. Though the transition Reynolds number of circular pipe flow has long been a matter of controversy, recently it has become evident that the transition Reynolds number can be defined as the Reynolds number at which the time for a puff to split and the

time for a puff to disappear are equivalent.

In two-dimensional channel flows, though a critical Reynolds number at which infinitesimal disturbances grow is predicted by linear stability theory, it is known that even at lower Reynolds numbers, there occurs a subcritical transition to turbulence due to a strong initial disturbance. Since the experimental facility for the two-dimensional channel flow is more complicated than that for circular pipe flow, the understanding of the two-dimensional channel flow has been less advanced. For example, the transition Reynolds number has not been determined.

In this study, we experimentally observed water channel flow around the transition Reynolds number to elucidate its subcritical transition. Furthermore, by adding polymers to the channel flow, the effects of polymer addition on the transition are clarified, and in turn, these effects are discussed for more understanding of the channel flow of the Newtonian fluid.

The experiment was conducted in a closed-loop channel flow apparatus. Water pressurized by a pump flow through a settling chamber and a nozzle into a channel about 7 m long. The flow is disturbed by a tripping wire installed upstream of the channel section, and the flow under the channel flow is sufficiently disturbed by narrowing the width in the span direction and increasing the Reynolds number downstream of the tripping wire. The spanwise width is increased again under the narrow channel, the Reynolds number of the flow decreases, and the flow flows into the test section. The channel section is made of glass for visual access. The pressure gradient was measured with a static pressure tube and pressure transducer, and the wall friction coefficient was calculated from the pressure gradient. Pearl pigment flakes were used as flow tracers for flow visualization. Polyacrylamide (PAM) was used as an additive in the polymer addition experiments. Aqueous polyacrylamide solutions are known to be non-Newtonian fluids with shear-thinning properties.

Experiments were first performed on a channel flow of water of a Newtonian fluid. Flow visualization revealed that as the Reynolds number increased from laminar flow conditions, turbulent spots began to appear randomly, and as the Reynolds number increased further, the turbulent spots transformed into oblique patches and turbulent bands that formed across the channel width, and between turbulent regions strong streaks appear. Image analysis was used to determine the intermittency rate, or the turbulence fraction in the flow, and it was found that the wall friction coefficient almost reached the turbulence value before the flow was completely turbulent. This suggests that the streaky structure observed in the non-turbulent region contributes to the enhancement of momentum transfer in the wall-normal direction. Large-scale structures consisting of irregular streaks were also observed in turbulent conditions where the intermittency ratio was nearly unity. These have an oblique shape similar to the non-turbulent/turbulent patches of the transition process, suggesting that the transition process is not complete even above the Reynolds number at which the entire flow is turbulent.

The same experiment was then conducted by adding polymer to the channel flow. The streamwise scales of the streaks in the non-turbulent region was estimated by calculating the autocorrelation coefficient of the visualized images shifted in the streamwise direction. The intermittency ratio was determined as a fiction of by apparent Reynolds number based on the apparent viscosity from the wall friction coefficient in the laminar case. The Reynolds number at which the intermittency increases rapidly shifts toward the higher Reynolds number with increasing the polymer concentration, indicating that the transition is delayed by polymer addition. Furthermore, the streaks appearing in the non-turbulent region elongate with the polymer addition, demonstrating that the polymer affects not only the transition Reynolds number but also the flow structure during the transition process. This strongly suggests that further study of the effects of polymer addition will lead to a better understanding of the mechanism of patch-like turbulent formation in transition channel flows of Newtonian fluids.