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Flow Separation at Inlet Causing Transition and Intermittency in Circular Pipe Flow

Masuro OGAWA

HTGR Research and Development Center
Oarai Research and Development Institute
Sector of Fast Reactor and Advanced Reactor Research and Development

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国立研究開発法人日本原子力研究開発機構 研究連携成果展開部 研究成果管理課
〒319-1195 茨城県那珂郡東海村大字白方 2 番地4
電話 029-282-6387, Fax 029-282-5920, E-mail:ird-support@jaea.go.jp

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2-4 Shirakata, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195 Japan
Tel +81-29-282-6387, Fax +81-29-282-5920, E-mail:ird-support@jaea.go.jp

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Masuro OGAWA

HTGR Research and Development Center, Oarai Research and Development Institute
Sector of Fast Reactor and Advanced Reactor Research and Development
Japan Atomic Energy Agency
Oarai-machi, Higashiibaraki-gun, Ibaraki-ken

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Transition phenomena from laminar to turbulent flow are roughly classified into three categories. The circular pipe flow of the third category is linearly stable against any small disturbance, despite that the flow actually transitions and the transitional flow exhibits intermittency. These issues are among the major challenges that are yet to be resolved in fluid dynamics. Thus, the author indicates for the first time the fact that nobody has ever noticed and recognized. This fact is “Flow in a circular pipe transitions from laminar flow because of the vortices released from separation bubble forming in the vicinity of the inlet of the pipe, and the transitional flow becomes intermittent because the vortex-shedding is intermittent”. The fact is supported by many experimental results that the entrance shape of a circular pipe largely affects the transition Reynolds number and that the flow between concentric double cylinders with the outer cylinder rotating dominantly, categorified also in the third transition phenomenon, exhibit intermittency due to the flow separation just as does the transitional flow in a circular pipe. Recognizing the fact, it can be easily explained why the linear stability theory has not been able to predict the transition in circular pipe flow, why the circular pipe flow actually transitions even due to small disturbance, why the transitional flow actually exhibits intermittency, and why numerical analysis has not been able to predict the intermittency of the transitional flow in a circular pipe. The author’s insight and indication in the present study has eliminated one of the biggest issues on transition flow that has been considered unresolved in fluid dynamics. The present study has clarified that the entrance shape of abruptly angular contraction types can makes the transition Reynolds number smaller as much as possible to promote heat transfer, which is one of the most important tasks of thermal fluid design in a High Temperature Gas-cooled Reactor.

Keywords: Flow Separation, Transition, Intermittency, Circular Pipe Flow, Vortex-shedding, High Temperature Gas-cooled Reactor, Heat Transfer Promotion, Inlet Shape

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円管内流れにおける遷移と間欠性を引き起こす入口での流れの剥離

日本原子力研究開発機構
高速炉・新型炉研究開発部門　大洗研究所
高温ガス炉研究開発センター
小川　益郎

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層流から乱流への遷移現象は、大きく三つの範疇に分類される。第 3 の範疇に分類される円管内流れは、流れが実際に遷移し、遷移流が間欠性を示すにもかかわらず、あらゆる小さな外乱に対して線形的に安定である。このことは、流体力学ではまだ解決されていない大きな課題の一つである。そこで、著者は、これまで誰も気がつかず認識してこなかった事実を初めて指摘する。この事実というのは、「円管内の流れは、流れの剥離によって、円管入り口付近に形成される剥離泡から放出された渦のために層流から遷移し、そして渦放出が間欠的であるために遷移流が間欠性を示す。」というものである。この事実は、円管の入口形状が遷移レイノルズ数に大きく影響することや、第 3 の遷移現象に分類されている外側円筒が支配的に回転する同心二重円筒間の流れが円管内の遷移流れと同様に流れの剥離によって間欠性を示すといった、多くの実験結果によって裏付けられている。この事実を認識すれば、なぜ線形安定性理論が円管内流れの遷移を予測できなかったのか、なぜ円管内流れが微小かく乱でも実際に遷移するのか、なぜその遷移流が実際に間欠性を示すのか、そしてなぜ数値解析が円管内の遷移流の間欠性を予測することができなかったのかを容易に説明することができる。本研究における著者の洞察と指摘によって、流体力学において未解決と考えられてきた遷移流に関する最大の問題の一つを消し去ることができた。本研究によって、高温ガス冷却炉の熱流体設計において最も重要な課題の一つである熱伝達促進のために、急縮小型の入口形状が遷移開始レイノルズ数をできる限り小さくできることを明らかにした。

大洗研究所：〒311-1393 茨城県東茨城郡大洗町成田町 4002

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1. Introduction

The phenomenon in which flow transitions from laminar to turbulent flow is roughly classified into three categories according to its transition mechanism [1]. The first transition phenomenon is observed in free shear flows with no solid boundary like jet, wake and separated flow, and in flow between double cylinders where rotation of the inner cylinder dominates that of the outer cylinder with sufficient length in the direction of the rotation axis and annulus width smaller than the radius (hereinafter referred to as flow between double cylinders with the inner cylinder rotating dominantly). These flows are unstable against small disturbances. The transition begins with a process in which only the specific disturbances grow among the energy spectrum of disturbances, and the disturbances composed of periodic components increase due to nonlinear interference between the disturbances and the mean flow. Then, these line spectra in the energy spectrum eventually become continuous spectra due to an increase in coincidence caused by nonlinear interference, turbulence is formed, and the transition is completed. This first transition phenomenon progresses relatively slowly, so named as “transition by spectral evolution” by Coles [2]. For example, in flow between double cylinders with the inner cylinder rotating dominantly, the transition reaches the final stage only after the angular velocity becomes ten times the angular velocity at which Taylor vortex occurs [1].

The second transition phenomenon is observed in flow between stationary semi-infinitely large parallel flat plates (hereinafter referred to as flow between stationary parallel flat plates) and in plate boundary layer flow. In these flows, the small disturbances are amplified by the relatively weak instability due to viscosity, and instantaneously unstable velocity distribution appears due to the nonlinear effect of the amplified disturbances. Turbulent spots are generated due to the two-dimensional characteristics of the velocity distribution and spread downstream, finally covering the entire flow passage, and the transition is completed. Thus, the second transition phenomenon is characterized by strong three-dimensionalization and abrupt rupture at the interface of the turbulent spots, contrary to the slow progression of the first transition phenomenon, and reveals the intermediate transition mechanism between the first transition phenomenon and the third one to be described next [1].

The last third transition phenomenon is observed in flow inside a long and straight pipe with a circular cross-section (hereinafter referred to as circular pipe flow) and in flow between double cylinders where rotation of the outer cylinder dominates that of the inner cylinder with sufficient length in the direction of the rotation axis and annulus width smaller than the radius (hereinafter referred to as flow between double cylinders with the outer cylinder rotating dominantly). Linear stability theory predicts that these flows are stable against small disturbances at any Reynolds number. Nonetheless, these flows have been observed to actually become turbulent. Observed at a spatially fixed point, these transitional flows also exhibit the intermittency in that laminar and turbulent regions alternately appear, and cause a catastrophic change at a thin interface between the laminar and turbulent regions [1]. Thus, the third transition phenomenon has been named as "catastrophic transition" by Coles [2], contrary to the first slow "transition by spectral evolution".

The main experimental studies to date on the circular pipe flow, which is the subject of the present paper, are reviewed below. First, it was started with a systematic experiment by Hagen [3] in 1855, and Reynolds [4] related the initiation of the transition to the Reynolds number in 1883 and took up "the flow" as a research subject for the first time. Ekman [5] has improved the experimental apparatus of Reynolds and succeeded in maintaining laminar flow up to Reynolds number of 44,000 in circular pipe flow. Next, In the 1970s, Wygnanski et al. [6,7] have investigated transitional flow in a circular pipe and presented the schematic diagram showing the relationship between the disturbance level at the inlet; u'/u_{ave} and the transition initiation and completion Reynolds numbers. Here, u' and u_{ave} are axial velocity fluctuation and axial average velocity, respectively, and Reynolds numbers at which a turbulent region begins to appear and at which all laminar regions disappear sufficiently downstream are called the transition initiation Reynolds number and the transition completion Reynolds number, respectively. It has been indicated in this schematic diagram that the transition initiation Reynolds number hardly changes and is about 2,000 for u'/u_{ave} greater than several percent, while the smaller u'/u_{ave} than about 0.4%, the higher the transition initiation Reynolds number.

Schematic diagrams of transitional flow in a circular pipe and velocity signals on the x axis downstream (x=L) of the circular pipe are shown in Fig.1 with the reference of the experimental result of the author et al. [8] The abscissa of Fig.1 (b) and (c) is time and the ordinate is u/u_{ave} on the axis of the circular pipe. Here, u is the axial velocity. As can be found from Fig.1 (b) and (c), axial velocity fluctuation; u' is little observed in the velocity signal, when the laminar region of the transitional flow passes through the observing point of $x = L$ on the axis. Here, x and L are the axial distance and the distance to the observing point, respectively. In the present paper, let's call the region of $x < 0$ as "entrance area" and the position of $x = 0$ as "inlet". The laminar region of the transitional flow has a parabolic radial velocity distribution and the flow velocity on the axis is a value twice the axial average velocity, such as with a fully developed laminar flow. On the other hand, velocity fluctuation is observed when the turbulent region passes through the observing point. The turbulent region has the radial velocity distribution of plug type and the flow velocity on the axis is a value about 1.3 times the axial average velocity, such as with a fully developed turbulent flow. The turbulent regions due to large and small disturbances at the inlet are distinguished as 'puff' (See Fig.1 (b)) and 'slug' (See Fig.1 (c)), respectively. The author et al. [8] have reported in the experiment on transition in circular pipe flow that the average length of the puff is 38 diameters under the condition of Re=2420, γ=0.50, and that of the slug is 280 diameters under the condition of Re=9460, γ=0.50. Here, Re is the Reynolds number and γ is an intermittent factor defined as the time proportion occupied by the turbulent region. γ=0 and γ=1 denote laminar flow and turbulent flow, respectively.

Typical entrance components connected to a circular pipe are shown in Fig.2. Here, r, D, W and φ are the radial distance, the inner diameter of a circular pipe, the flange diameter and the angle formed between the flange surface and the x axis, respectively. One entrance configuration used in experiments generally includes entrance shape, transition promotion device and disturbance suppression device. Typical entrance shapes are an abruptly angular contraction type like a flange type with the diameter of W as shown in Fig.2 (a) and (b), and a gradually curved contraction type like a bellmouth type and a circle type as shown in Fig.2 (c) and (d), respectively. The angle; φ in Fig.2 (a) is φ=90 degrees and in Fig.2 (b) 0 degree<φ<90 degrees. The entrance shape is connected to a circular pipe at the inlet (x=0). The transition promotion devices like orifice, disk and jet injection are equipped at the inlet as shown in Fig.2 (e), (f) and (g), respectively. The disturbance suppression devices like honeycomb and screen are equipped in the flow passage of the entrance area (x<0) as shown in Fig.2 (i).

Wygnanski et al. [6] have reported that the transition initiation Reynolds number is 17,500 in the circular pipe connected to the circle and bellmouth entrance shapes with sufficiently gradually curbed contraction type installed with honeycomb (hereinafter referred to as No.1 entrance configuration) to suppress disturbances at the inlet. On the basis of the No.1 entrance configuration, the transition initiation Reynolds number has been reported to reach 45,000 by use of screen added to further suppress the disturbances, and conversely, to decrease down to 2,000 by use orifice or disk (hereinafter referred to as No.2 entrance configuration) to artificially promote transition. Also, Wygnanski et al. [6] have reported that in the No.1 entrance configuration described above, the disturbance level; u'/u_{ave} at the center and the 15 diameters downstream of the inlet (r=0 and x=15D) of the circular pipe was 0.17% at Reynolds number of 10,000 and 0.16% at Reynolds number of 19,000 higher than the transition initiation Reynolds number of 17,500, while in the No.2 entrance configuration, the u'/u_{ave} was 7.8% at Reynolds number of 2,400. Thus, it is found that even small disturbance at the inlet makes circular pipe flow transition and the transitional flow exhibits intermittency.

Takeno et al. [9] have examined the influence of the entrance shape on the transition initiation Reynolds number and have reported that the transition initiation Reynolds numbers are 2,100, 3,400 and 8,800 for the entrance shapes like Fig.2 (a), (b) and (d), respectively. Their entrance shape of Fig.2 (b) was W=2D and φ=55 degrees. Here, W is the diameter of the flange (See Fig.2 (a)). Thus, it is understood that the transition Reynolds number also greatly differs with varying entrance shapes in case of the same disturbance level at the inlet. The author et al. [8] have presented in the experiment that in a circular pipe with various entrance configurations, the pressure loss coefficient and the heat transfer coefficient of the transitional flow could be calculated from those of laminar and turbulent flows by using the intermittent factor; γ. The author et al. [10, 11] have reported in the experiments that when gas flow in a circular pipe was heated up, it began to exhibit intermittency similar to isothermal transitional flow with a certain heating rate and so it actually laminarized from turbulent flow. Further strongly heating, the gas flow has been reported to completely become laminar flow from the signals of hot-wire anemometer at the outlet even when the bulk Reynolds number at the outlet corresponds to turbulent flow. Here, the bulk Reynolds number is the Reynolds number calculated from the physical properties at the cross-sectional average temperature. Also, the numerical analysis using a two-equation turbulence model has shown that this laminarization phenomenon would occur not only by acceleration of flow due to gas expansion but also by suppression of disturbances due to increase in viscosity in the vicinity of the inner surface of the circular pipe.

After those, a number of researchers have examined the turbulent structure of puff and slug. For example, in 2008, Nishi et al. [12] have measured in detail how puff and slug develop axially using the experimental apparatus that could freely control the transition Reynolds number by installing a diaphragm at the inlet of circular pipes with nine different pipe-lengths from 33.3 to 533.3 diameters. The relationship between Reynolds number and the velocity of the leading and the trailing edges of turbulent region, independency of the slug structure on the nature of disturbance, the minimum transition initiation Reynolds number of 1,940 and so on have been reported. In 2011, Avila et al. [13] have proposed the definition of the critical value at which the subcritical transition, which will be described later, occurs in so-called the base flow which is linearly stable in a circular pipe, and have reported that the Reynolds number is 2,040 ± 10 at which the mean splitting time of puff and the mean lifetime until turbulence decays become equal. They have concluded that their approach to determine the onset and sustainment of turbulence should be equally applicable even though details of mechanisms in free shear flows may differ from case to case.

On the other hand, in the linear stability theory, it has been reported that circular pipe flow is predicted to be stable at any Reynolds number against the axisymmetric small disturbances by Sexl [14] in 1927, Corcos et al. [15], Gill [16], Davey et al. [17] and also against the nonaxisymmetric small disturbances by Lessen et al. [18], Salwen et al. [19], Grag et al. [20] and Salwen et al. [21]. Then, Tatsumi [22] in 1952, Huang et al. [23], Sarpkaya [24] and Grag [25] have considered that the circular pipe flow transitions because it would become unstable against disturbances with finite amplitude (hereinafter referred to as finite amplitude disturbance), and investigated the instability of small disturbances due to underdevelopment of the developing flow in the upstream as a cause producing the finite amplitude disturbances. As a result, although the critical Reynolds number surely exists, its value is extremely high, not the low transition Reynolds number as experimentally measured. Thus, in the bifurcation problem of the solution in the Navier-Stokes nonlinear differential equations called the supercritical transition problem, linear theory and weakly nonlinear theory couldn't find the critical point (also called as bifurcation point) at which transition is triggered. Therefore, instability of laminar flow due to finite amplitude disturbance has been investigated. However, Itoh [26] in 1977 and Patera et al. [27] have reported that circular pipe flow is stable against the axisymmetric finite amplitude disturbances, and Orszag et al. [28] has confirmed that also in the time-dependent secondary instability of the axisymmetric finite amplitude disturbance, although three dimensional disturbances have showed strong exponential amplification, those are blocked by strong decay of the axisymmetric finite amplitude disturbances. In addition, nonlinear effect of nonaxisymmetric small non-normal disturbance has been investigated, but it has been reported that the nonlinear effect works to suppress amplification of disturbances in the case that the axial wave number is not zero by O'Sullivan et al. [29] and in the other case that the axial wave number is zero by Bergström [30].

Under such circumstances, Nagata [31] has reported in 1990 that in numerical analysis, exact three-dimensional steady-state solution of Navier-Stokes equations exists except for the well known laminar flow solution of linear velocity distribution in flow between parallel flat plates in which one of them moves at a constant speed (hereinafter referred to as flow between one-side driven parallel flat plates). He has reported that the solution exists many, each bifurcating at a certain Reynolds number, and the solution on each bifurcation line reveals a velocity distribution close to that of turbulence in which steady longitudinal vortices exist and momentum exchange occurs due to not only shear but also vortices. These solutions are interesting in that they indicate not only that laminar flow solution of Navier-Stokes equations is not unique but also that there is a pseudo turbulent flow including vortex tubes between laminar and turbulent flows. With the discovery of nonlinear steady-state solutions in flow between one-side driven parallel flat plates by Nagata [31] and Dauchot et al. [32] as an initiator, the interest of researchers has shifted to so-called subcritical transition problem, which is an essentially nonlinear problem caused by finite amplitude disturbance exceeding about 1% in laminar flow such as flow between stationary parallel flat plates far away from the critical point and in linearly stable flow with no critical point such as flow between one-side driven parallel flat plates, square duct flow and circular pipe flow.

In 2000, also in circular pipe flow, more than twenty nonlinear three-dimensional steady-state traveling wave solutions have been discovered by Faisst et al. [33], Wedin et al. [34] and Pringle et al. [35, 36]. Against small disturbances, the transition phenomenon until completion of the transition experiences through a three-dimensionally destabilizing process at the stage that the Tollmien-Schlichting wave of two-dimensional disturbance propagates downstream. While, in circular pipe flow artificially given finite amplitude disturbances exceeding about 1%, turbulence structure during generation, growth and decay have been reported in the so-called bypass transition, that is, the transition not experiencing through the process of generation and growth of the Tollmien-Schlichting wave. Schneider et al. [37] have reported that unstable direction of steady-state traveling wave solution exists two or more and the flow behavior becomes chaos in the bypass transition where turbulent spots spatially grow while generating the streak structure and quasi-longitudinal vortex structure chain-wise.

In 2011, Mullin [38] has reviewed studies on circular pipe flow so far that "Linear stability of Hagen Poiseuille flow has yet to be proved, but all theoretical and numerical works indicate that this is the case and all experimental evidence supports linear stability; i.e., there is no definite critical Reynolds number for the onset of turbulence.".

In parallel with the above-mentioned studies aiming to theoretically elucidate the transition phenomenon, in accordance with the remarkable evolution of the computer, attempts have begun to directly predict the transition to turbulence by direct numerical simulation (hereinafter abbreviated as DNS) without any turbulence model. For example, in 1999, Shan et al. [39] have artificially created intermittency by temporally changing the disturbance at the inlet and examined the structure of puff and slug. They have reported that the results of the DNS on the velocity of leading and trailing edges of puff and slug, and the puff and slug structures, the recirculation pattern observed at the leading and trailing edges and so on agree well with the experimental results obtained thus far. The above-mentioned bypass transition doesn't homogeneously occur, but temporally and spatially localized turbulence exhibits a non-equilibrium critical phenomenon, and the length scale of the chaotic behavior is about the length of the puff / slug measured in experiments. Therefore, it is required to simulate the flow in the large area, not the so-called minimal flow, which is flow in the small periodic box proposed by Jimenez et al. [40] In response to this situation, studies of large-scale DNS have been already started on subcritical transition problems such as flow between one-side driven parallel flat plates, square duct flow and circular pipe flow. In 2015, Wu et al. [41] have given the finite amplitude disturbance at the inlet of the circular pipe with 125 diameters length and have performed DNS on the transitional flow. They have investigated the growth rate of the disturbance energy and the development of the vortex structure in the axial direction, and have reported that the energy norm grows exponentially rather than algebraically with the inlet disturbance given, and then the localized disturbance causes a gradual transition, finally the flow becomes the fully developed turbulent flow. And, they have suggested that "Some of the previously attributed abruptness and the mysteriousness are perhaps due to the inability to study the process accurately with very fine spatial and temporal resolution".

On the other hand, the intermittency in transitional flow is also called "turbulent-laminar pattern" or "turbulence stripe" in various papers on the transition. Existence of the intermittency in transitional flow has been confirmed, beginning with circular pipe flow, then in flow between double cylinders with the outer cylinder rotating dominantly, to flow between one-side driven parallel flat plates, flow between stationary parallel flat plates, flow between parallel circular disks and so on. With the progress of research on the subcritical transition in recent years, in 2010, Tsukahara et al. [42] has performed DNS of a large scale computation area in flow between stationary parallel flat plates, and has predicted the turbulent-laminar pattern (intermittency) in subcritical transitional flow due to finite amplitude disturbance. However, in a circular pipe, the intermittency of the transitional flow due to finite amplitude disturbance has not yet been predicted by DNS. It is an important fact that the transitional flow actually exhibits intermittency even due to small disturbance at the inlet as reported by Wygnanski et al. [6], and the fact should not to be overlooked.

Thus, the universal understanding has not yet been attained concerning the elementary process or essence of transition phenomenon common to flows of which the basic flow is linearly stable such as flow between single-side driven parallel flat plates, square duct flow and circular pipe flow. In 2016, studies on the universality of such a transition phenomenon have been performed in flow between stationary parallel flat plates by M. Sano et al. [43] and in flow between one-side driven parallel flat plates by G. Lemoult et al. [44] Their experimental and numerical analyses have concluded that the flow transition phenomenon belongs to universality class which is identified in the phase transition phenomenon called directed percolation phenomenon similar to propagation phenomena of disease, forest fire and intracellular calcium because the critical exponents obtained in each flow of their experiments agree with the universal critical exponents of the directed percolation phenomenon. It has been made clear that the directed percolation phenomenon, which is said to be typical of phase transition in non-equilibrium systems, forms the universality class because various mathematical models have the same critical exponents as the directed percolation phenomenon. In the directed percolation phenomenon, when the propagation probability (the critical exponent) exceeds a certain value, the active state embedded among the inactive states starts to propagate without disappearing, and finally all the inactive states transition to the active state. The inactive state doesn't naturally transition to the active state. Speaking of the transitional flow, linearly stable laminar flow that doesn't naturally transition to turbulence corresponds to the inactive state, and turbulent flow corresponds to the active state. The studies done by M. Sano et al. [43] and G. Lemoult et al. [44] have revealed that the completion of transition to turbulence could be represented by the critical exponents of the directed percolation phenomenon and that the flow transition phenomenon could be also explained as a phase transition phenomenon in universal non-equilibrium systems. However, these studies have not mentioned anything as to why turbulence (active state) began to appear in the flow, although those have clarified in what kind of state the flow becomes turbulent.

In circular pipe flow, D. Barcley [45] has presented in 2016 following above the studies that all stages of the transition process from transient turbulence to final fully developed turbulent flow can be understood from relatively few physical features and two-variable model. Also, he has concluded that the essential coupling between turbulence and the mean shear in the transitional flow is missed in the mapping onto the problem of coexisting phases, that the near-perfect analogy is instead excitable and bistable media, and that the process in the route to turbulence in circular pipe flow is fundamentally a transition from excitability to bistability. But, his study did not answer the questions why circular pipe flow actually transitions even due to small disturbance and why the transitional flow actually exhibits intermittency.

It is being considered that the linearly stable flow transitions from laminar flow because of its instability against finite amplitude disturbances. However, as reported by Wygnanski et al. [6] , small disturbance at the inlet makes circular pipe flow transition, and the transitional flow exhibits intermittency. Thus, there still remain the issues of "Why does circular pipe flow actually transition from the linearly stable laminar flow, even due to small disturbances not finite amplitude disturbances? And, why does the transitional flow exhibit intermittency?" Therefore, the author indicates for the first time the fact that nobody has ever noticed and recognized and that can resolve these issues.

2. Flow separation causing transition and intermittency in circular pipe flow

In circular pipe flow, as described in the previous chapter, the following two issues are among the major challenges that have yet to be resolved in fluid dynamics.

Issue 1: First, let's take up a circular pipe connected to the entrance shape of a sufficiently gradually curved contraction type with disturbance suppression devices like honeycomb and screen (See Fig.3 (b) described later). The disturbances at the inlet of this circular pipe are sufficiently suppressed with disturbance suppression devices, at least are not intentionally produced. In general, it has been considered that the transition in linearly stable flow in a circular pipe is caused by instability against finite amplitude disturbances. However, as pointed out at the end of the previous chapter, it has not yet been clarified how the finite amplitude disturbances are actually produced in various entrance shapes and why the linearly stable flow actually transitions from laminar flow due to small disturbance at the inlet. Thus, it is not yet theoretically clarified why the flow actually transitions from the laminar flow even due to small disturbance at the inlet.

Issue 2: Transitional flow in a circular pipe exhibits the intermittency in that laminar region and turbulent region occupying the entire cross-section of the circular pipe alternately pass through at the fixed observation points downstream. In recent years, the intermittency observed in subcritical transition caused by finite amplitude disturbance was predicted by using DNS in a large scale computation area in flow between stationary parallel flat plates. However, due to small disturbance at the inlet, transitional flow in a circular pipe actually exhibits intermittency as reported by Wygnanski et al. [6] Thus, it is not yet theoretically elucidated why the transitional flow in the circular pipe also actually exhibits intermittency even due to small disturbance at the inlet.

2.1 The factual recognition resolving two issues

In order to resolve the above two issues at the same time, the author indicates for the first time the fact that nobody has ever noticed and recognized. This fact is "Flow in a circular pipe transitions from laminar flow because of the vortices released from separation bubble forming in the vicinity of the inlet of the pipe, and the transitional flow becomes intermittent because the vortex-shedding is intermittent".

2.1.1 Answer for Issue 1

The circular pipe flow actually transitions from laminar flow due to disturbance of vortices released from the separation bubble forming in the vicinity of the inlet of the pipe when the Reynolds number exceeds a certain value. Flow in a circular pipe always separates in the vicinity of the inlet with a certain Reynolds number, regardless of any entrance shape shown as Fig.2 (a) to (d). Therefore, circular pipe flow transitions, even though it is linearly stable. This flow separation at the inlet of a circular pipe is a well-known phenomenon that anyone notices and recognizes, if it is pointed out.

The transition in circular pipe flow could not be predicted in the linear stability theory so far because separation in the vicinity of the inlet has not been considered in the linear stability theory. And in the experiments up to now, circular pipe flow has necessarily transitioned from laminar to turbulent flow because one could not manufacture any entrance shape such that the flow doesn't separate in the vicinity of the inlet. If the entrance shape which doesn't cause any separation even at high Reynolds numbers could be manufactured, the circular pipe flow would remain laminar at any Reynolds number against small disturbances, just as the linear stability theory predicts.

2.1.2 Answer for Issue 2

The transitional flow in a circular pipe actually exhibits the intermittency, in which the laminar region and the turbulent region are alternately observed, because the vortex-shedding from the separation bubble intermittently occurs within a certain range of Reynolds numbers. Further increasing the Reynolds number, the vortex-shedding becomes continuous, consequently the laminar region disappears from the flow, that is, the transition to the turbulent flow is completed. Transitional flow in a circular pipe actually exhibits intermittency not due to finite amplitude disturbance but even due to small disturbance at the inlet because separation necessarily occurs in the vicinity of the inlet even for entrance shape of any sufficiently gradually curbed contraction type installed disturbance suppression devices.

The intermittency observed in the transitional flow in a circular pipe could not be predicted in numerical simulations so far because the entrance area ($x<0$) of the circular pipe was not included in the numerical computation area. In the numerical simulations performed so far, flow velocity distribution of the fully developed laminar or turbulent flow, or uniform flow velocity distribution is given at the inlet ($x=0$) of the circular pipe, and the separation caused by the entrance shape has not been taken into consideration.

2.2 Support of the present factual recognition

Some experimental results obtained earlier which support the present factual recognition are listed in the following.

2.2.1 Experimental result on that the entrance shape of a circular pipe largely affects the transition Reynolds number

It is well known that the disturbance level at the inlet greatly affects the transition initiation / completion Reynolds number in circular pipe flow under the same entrance shape. On the other hand, it is also clear that the difference in entrance shape greatly affects the transition Reynolds number under the same disturbance level. For example, as mentioned in the previous section, Takeno et al. [9] have examined the influence of the entrance shape on the transition initiation Reynolds number. They have reported that the transition initiation Reynolds numbers are 2,100 for the entrance shape like Fig.2 (a), 3,400 for like Fig.2 (b) and 8,800 for like Fig.2 (d). Thus, the entrance shape of more abruptly angular contraction type makes the transition Reynolds number decrease, and conversely the entrance shape more gradually curved contraction type makes it increase. Concerning the influence of the diameter W of the flange (See Fig. 2 (a)), transition initiation Reynolds numbers were 1,990 and 2,800 for W=6.2D and W=1.5D, respectively, from the experimental results by the author et al. [8, 9], and it is found that smaller W leads to larger transition initiation Reynolds number. It is obvious that the transition Reynolds number largely varies depending on the entrance shape including the size of W.

Well, why does the difference in entrance shape of a circular pipe largely affect the transition Reynolds number? The answer is because Reynolds number at which the vortices are released from separation bubble forming in the vicinity of the inlet of the pipe differs depending on the entrance shape. Namely, the entrance shape determines the Reynolds number at which the vortex-shedding from separation bubble begins. The smaller value of φ in the range of $\varphi<90$ degrees in the entrance shape of angularly abrupt contraction type (see Fig.2 (c)), and the more gradual entrance shape of curved contraction type, the later the separation occurs, therefore the Reynolds number, at which the vortex-shedding from the separation bubble begins to occur, becomes higher. As a result, the transition initiation Reynolds number also increases. Thus, this is one of firm supports of the present fact recognition that flow separation causes transition and intermittency in circular pipe flow.

Circular pipe flow is linearly stable against small disturbances at the inlet as reviewed by Mullin [38]. According to theoretical analyzes [33-36], finite amplitude disturbance given at the inlet of a circular pipe causes the bypass transition in linearly stable flow. Let's consider the finite amplitude disturbance in the entrance configuration with entrance shape of gradually curved contraction type and disturbance suppression devices. In this entrance configuration, with a small Reynolds number, the disturbances at the inlet will remain small in the range of small Reynolds numbers. Then, how do the small disturbances at the inlet grow into finite amplitude disturbances and reach the critical finite amplitude disturbance that makes the circular pipe flow transition? One may answer "As the Reynolds number is increased, the disturbances at the inlet also become larger and larger, eventually reach the critical finite amplitude disturbance".

Here, let's consider two entrance configurations with entrance shapes of flange type and bellmouth type as shown in Fig.3 (a) and (b), respectively. The disturbances at the inlet (x=0) are sufficiently suppressed by honeycomb and screen. Referring to the results of many previous experiments, let the transition initiation Reynolds numbers for the entrance shapes of flange and bellmouth types be roughly 2,000 and 10,000 respectively. A fact that the circular pipe flow transitions at the Reynolds number of 2,000 for the entrance shape of flange type as shown in Fig.3 (a) means that disturbances at the inlet reaches the critical finite amplitude disturbance at the Reynolds number of 2,000. Therefore, even if the entrance shape of bellmouth type as shown in Fig.3 (b) is installed instead of the flange type, disturbances at the inlet should reach the critical finite amplitude disturbance with the same Reynolds number of 2,000, as that for the entrance shape of flange type. However, in the entrance shape of bellmouth type, the disturbances at the inlet have not yet reached the critical finite amplitude disturbances even at the Reynolds number of 2,000 because its transition initiation Reynolds number is 10,000. Thus, contradiction arises assuming that the circular pipe flow transitions due to the presence of the finite amplitude disturbance at the inlet. The present factual recognition on occurrence of flow separation can explain that circular pipe flow transitions at the Reynolds number of 2,000 for the entrance shape of flange type and 10,000 for bellmouth type, even if small disturbance doesn't reach the critical finite amplitude disturbance at the inlet.

The difference in entrance shape might be quantitatively expressed by the V_{SP}/u_{ave} of the radial flow velocity at the separation point normalized by axial average velocity. Here, V_{SP} is a radial flow velocity at the separation point. In order to analyze the influence of the entrance shape in the numerical simulation in the future, it is conceivable to include the whole entrance shape in the numerical computation area or simply to give the radial flow velocity V_{SP} at the inlet of the circular pipe.

2.2.2 Experimental results on that the puff appears even by using the transition promotion device

It is well known that even if disturbances at the inlet are suppressed by disturbance suppression devices like honeycomb and screen, the turbulent region of the transitional flow in the circular pipe becomes puff due to the entrance shape as shown in Fig.3 (a). On the other hand, in the entrance configuration of a gradually curved contraction shape with disturbance suppression devices as shown in Fig.3 (b) where the transition initiation Reynolds number exceeds 10,000 such as the experiments by Wygnanski et al. [6] and Nishi et al. [12], additionally installed transition promotion device such as orifice or disk as shown in Fig.2 (e) or (f) makes the transition initiation Reynolds number decrease down to around 2,000, and the turbulent region in the transitional flow also becomes puff.

Why not only in the entrance shape of abruptly angular contraction type but also in the entrance shape of gradually curbed contraction type with transition promotion device does the turbulent region of the transitional flow become puff?

With reference to numerous experiments so far, the main methods to make puff appear in a circular pipe at Reynolds number as low as 2,000 are listed below.

Method 1: A method using the entrance shape of the abruptly angular contraction type with large flange diameter as shown in Fig.2 (a).

Method 2: A method injecting jet from the pipe wall into the circular pipe flow as shown in Fig.2 (g).

Method 3: A method placing orifice or disk at the inlet as a transition promotion device as shown in Fig.2 (e) or Fig.2 (f), respectively.

Method 4: A method making the inner surface of the circular pipe rough.

The three basic shapes that cause separation observed in free shear flow are shown in Fig.4 (a), (b) and (c). The abruptly angular contraction type of Method 1 corresponds to the basic shape shown in Fig.4 (a). The jet injection of Method 2 makes separation occur, therefore corresponds to the basic shape shown in Fig.4 (a) as in Method 1. The orifice or disk of Method 3 corresponds to the shape as shown in Fig.4 (a)+(b) combining two basic shapes of Fig.4 (a) and (b). The orifice or the disk is the above combined shape placed on the inner wall surface or in the flow passage of the circular pipe, respectively. The flow separates on a rough surface manufactured by, for example, fine wires arranged so as to be orthogonal to the flow, and the disturbances are remarkably amplified by the unstable velocity distribution having an inflection point in the separation bubble, then the flow transitions. Klebanoff et al. [46] has reported that the separation caused by two-dimensional roughness is the main mechanism which promotes the transition. This suggests that the rough surface of Method 4 may be regarded as a miniaturized shape of the orifice of Method 3 and corresponds to the combined shape of Fig.4 (a)+(b). As described above, any Method 1 to 4 which makes puff appear in a circular pipe at Reynolds number as low as 2,000 causes separation corresponding to Fig.4 (a) or Fig.4 (a)+(b). Therefore, the turbulent region of the transition flow becomes puff due to transition promotion device installed in the inlet of the circular pipe with the entrance shape of gradually curved contraction type because vortex-shedding from separation bubble is caused at low Reynolds number of about 2,000, in the same way as in the entrance shape of abruptly angular contraction type, the jet injection and the roughness of the inner wall surface. As described above, the present factual recognition also can explain that the transitional flow in the circular pipe with the transition promotion device of not only Method 3 but also Methods 2 and 4 becomes puff. It should be verified in the future that the turbulent region might become slug for the entrance shape with the convex surface and the non-fixed separation point as shown in Fig.4 (c). Also in the transition of the other flows, separation at the inlet should be noted.

Conversely, it is highly likely that the reverse methods of Methods 1 and 2 don't make the flow in the circular pipe transition. It is conceivable as a reverse method of Method 1 to let φ and the wall thickness at x=0 of a circular pipe be as close as possible to 180 degrees and to zero, respectively, as shown in Fig.2 (j). It is conceivable as a reverse method of Method 2 to provide suction ports at the inlet as shown in Fig.2 (h) to suck the separation bubble or the disturbance therein. In fact, the transition initiation Reynolds number of

100,000 in the suction experiment has been reported by Pfenninger [47].

The basic shape of Fig.4 (a) like an entrance shape of abruptly angular contraction type and jet injection has a separation point S fixed at the corner of the inlet (x=0). The basic shape of Fig.4 (b) also has a fixed separation point S and has a reverse flow region observed in wake. On the other hand, the basic shape of Fig.4 (c) has a separation point S that would move according to the Reynolds number and the curvature of the entrance shape. Due to these differences in the basic shape, it is likely that some difference in characteristics appears in the transitional flow of a circular pipe, other than the difference in transition Reynolds number. Hof et al. [48] has reported in the jet injection experiment corresponding to the basic shape of Fig.4 (a) that the disturbance intensity was proportional to the minus first power of the transition initiation Reynolds number. On the other hand, Nishi et al. [12] have reported in the experiment using the orifice corresponding to the basic shape of Fig.4 (a)+(b) that the dimensionless disturbance intensity was proportional to the minus 0.5 power of the transition initiation Reynolds number.

2.2.3 Experimental results on that flow between double cylinders with the outer cylinder rotating dominantly also exhibits intermittency

It has been reported by Coles [2] that the flow between double cylinders with the outer cylinder rotating dominantly, which is classified into the third transition phenomenon, actually transitions to turbulence as the angular velocity becomes larger, although it is also linearly stable against small disturbances. In the transitional flow, the structure, in which the laminar flow region and the turbulent region are adjacent to each other through an interface therebetween, is observed, and the interface is propagated at an angular velocity somewhat smaller than that of the outer cylinder. Observing at a spatially fixed point shows that the laminar region and the turbulent region appear intermittently. In flow between double cylinders with the outer cylinder rotating dominantly, separation occurs on the convex outer surface of the inner cylinder as shown in Fig.4 (c) which is a shear boundary surface, although in flow between double cylinders with the inner cylinder rotating dominantly, separation doesn’t occur in the concave inner surface of the outer cylinder which is a shear boundary surface. Therefore, the flow between double cylinders with the inner cylinder rotating dominantly is classified not into the third transition phenomenon but into the first transition phenomenon. Thus, the flows both in the circular pipe and between double cylinders with the outer cylinder rotating dominantly have the shape of flow passage necessary to trigger separation. Therefore, according the present factual recognition, it can be explained that both the transitional flows, which are classified into the third transition phenomenon, exhibit the intermittency because the vortex-shedding from separation bubble is intermittent.

2.2.4 Intermittency frequency

It has been reported in the experiment [8] on transitional flow in a circular pipe that the intermittency frequency of the transitional flow, that is, the vortex-shedding frequency F was F=1.23 at γ=0.50 and Re = 2420. Let us estimate the vortex-shedding frequency of circular pipe flow according to that the vortex-shedding frequency is expressed by the equation of $F=0.6U_\infty/L$ in separation flow at leading edge of a thick flat plate [49]. Here, U_∞ and L are the average flow velocity and the separation bubble length in the leading edge separation flow of a thick flat plate, respectively. It has been reported that L becomes a constant length of about 10H in separation flow at leading edge of a thick flat plate even if Reynolds number increases [50] and that turbulent regions in circular pipe transitional flow localized gradually downstream about 60 diameters from the inlet of the circular pipe and were formed [51]. Here, H is a thickness of a thick flat plate. From these experimental results, $U_\infty=u_{ave}$ and L=60d are assumed in circular pipe flow. The vortex-shedding frequency F in circular pipe transitional flow is $F=0.6u_{ave}/60d$, and can be expressed as $F=0.01\nu Re/d^2$ using Reynolds number. Substituting the experimental values ;Re=2,420, $d=1.94\times10^{-2}$ m and $\nu=1.54\times10^{-5}$ m^2/s in the above the experiment [8] on transitional flow in a circular pipe into this equation of F, F=1.01 is estimated. Here, ν is kinematic viscosity. Thus, it is found that the intermittency frequency of the transition flow in a circular pipe, that is, the estimated vortex-shedding frequency of F=1.01 is not significantly different from the vortex-shedding frequency F=1.23 obtained in the experiment. Also from this, it is clear that flow separation causes circular pipe flow to transition.

3. Conclusion

It has not been theoretically predicted until now that the circular pipe flow actually transitions from laminar to turbulent flow under the entrance configuration with sufficiently gradually curbed contraction shape and with disturbance suppression devices.

Also, it has not been predicted in theoretical or numerical analysis that the transitional flow exhibits the intermittency in that laminar and turbulent regions occupy the entire cross section of the circular pipe and alternately pass through. Concerning these two outstanding issues in fluid dynamics, the author indicated for the first time the fact that nobody has ever noticed and recognized. This fact is “Flow in a circular pipe transitions from laminar flow because of the vortices released from separation bubble forming in the vicinity of the inlet of the pipe, and the transitional flow becomes intermittent because the vortex-shedding is intermittent”.

The present fact is supported by many experimental results on the following three facts.

(1) The difference in entrance shape greatly affects the transition initiation Reynolds number because the Reynolds number, at which the vortex-shedding from the separation bubble forming in the vicinity of the inlet begins, varies with the entrance shape, namely the transition initiation Reynolds number varies.

(2) The transitional flow in a circular pipe becomes puff not only by the entrance shape of an

abruptly angular contraction type but also by such a transition promoting device as orifice or disk placed at the inlet of a circular pipe connected to an entrance shape of gradually curbed contraction type, because the separation is caused at Reynolds number as low as 2,000 by the transition promotion device just as in the case of the abruptly angular contraction type.

(3) The transitional flow between double cylinders with the outer cylinder rotating dominantly classified into the third transition phenomenon exhibits intermittency, as in a circular pipe flow, because separation occurs on the convex outer surface of the inner cylinder which is a shear boundary surface.

According to the present factual recognition, it has become possible to explain the following four issues unresolved until now.

- The transition in circular pipe flow has not been predicted with the linear stability theory because separation in the vicinity of the inlet has not been considered in the theory.
- In the experiments up to now, circular pipe flow has apparently transitioned from laminar to turbulent flow because one could not manufacture any entrance shape such that the flow doesn't separate in the vicinity of the inlet. If an entrance shape that doesn't cause separation at any high Reynolds number could be manufactured, the circular pipe flow would remain laminar at any Reynolds number as the linear stability theory predicts.
- Transitional flow in a circular pipe exhibits intermittency not due to finite amplitude disturbance but even due to small disturbance at the inlet because separation necessarily occurs in the vicinity of the inlet even for entrance shape of any sufficiently gradually curbed contraction type installed disturbance suppression devices.
- Numerical simulations have to date failed to observe the intermittency in the transitional flow in a circular pipe because the entrance area ($x<0$) has not been included in the numerical computation area. In the numerical analysis, velocity distribution of developed laminar / turbulent flow or uniform velocity distribution has always been given as input condition at the inlet ($x=0$). Consequently, the separation due to the effect of an entrance shape has been ignored.

The author has just clarified that the transition phenomenon in circular pipe flow and flow between double cylinders with the outer cylinder rotating dominantly, which have been classified into the third category, is caused by flow separation. The present author's insight and indication has eliminated one of the biggest issues on transition flow that has been considered unresolved in fluid dynamics. In circular pipe flow and flow between double cylinders with the outer cylinder rotating dominantly, if it is possible not to cause flow separation, the both flows remain laminar even though Reynolds number increases, as predicted by the linear stability theory. The flows transition even if small disturbance only exists because the vortices released from separation bubble create finite amplitude disturbance. Recent DNS studies have shown that finite disturbance at the inlet of a circular pipe causes transition in linear stable flow. Also, recent theoretical studies have shown that transition phenomenon in circular pipe flow could be also predicted as a phase transition phenomenon called directed percolation phenomenon in universal non-equilibrium systems. In the directed percolation phenomenon, when the propagation probability (the critical exponent) exceeds a certain value, the active state embedded among the inactive states starts to propagate without disappearing, and finally all the inactive states transition to the active state. The inactive state doesn't naturally transition to the active state. Speaking about the transitional flow, finite amplitude disturbance exceeding a certain value makes linearly stable laminar flow (corresponding to 'inactive state'), which doesn't naturally transition to turbulence, transition to turbulent flow (corresponding to the active state).

Until now, many researchers have examined the process of decay and growth of intermittent puffs and slugs along the axial direction of the circular pipe. This is so important. On the other hand, the present study raises a new point of view that the intermittency of the puffs and slugs of transitional flow or the continuity of the final fully developed turbulence is greatly influenced by the intermittency or the continuity of vortex-shedding from separation bubble at the inlet of the circular pipe. Namely, the point of view is that the characteristics of vortex, vortex-shedding and so on from separation bubble at the inlet should be taken into consideration for transitional flow in a circular pipe, especially for practical use.

The present study has clarified that the entrance shape of abruptly angular contraction types like a flange type with W enough bigger than D as shown in Fig.2 (a) can make the transition initiation Reynolds number smaller as much as possible to promote heat transfer, which is one of the most important tasks of thermal fluid design in a High Temperature Gas-cooled Reactor.

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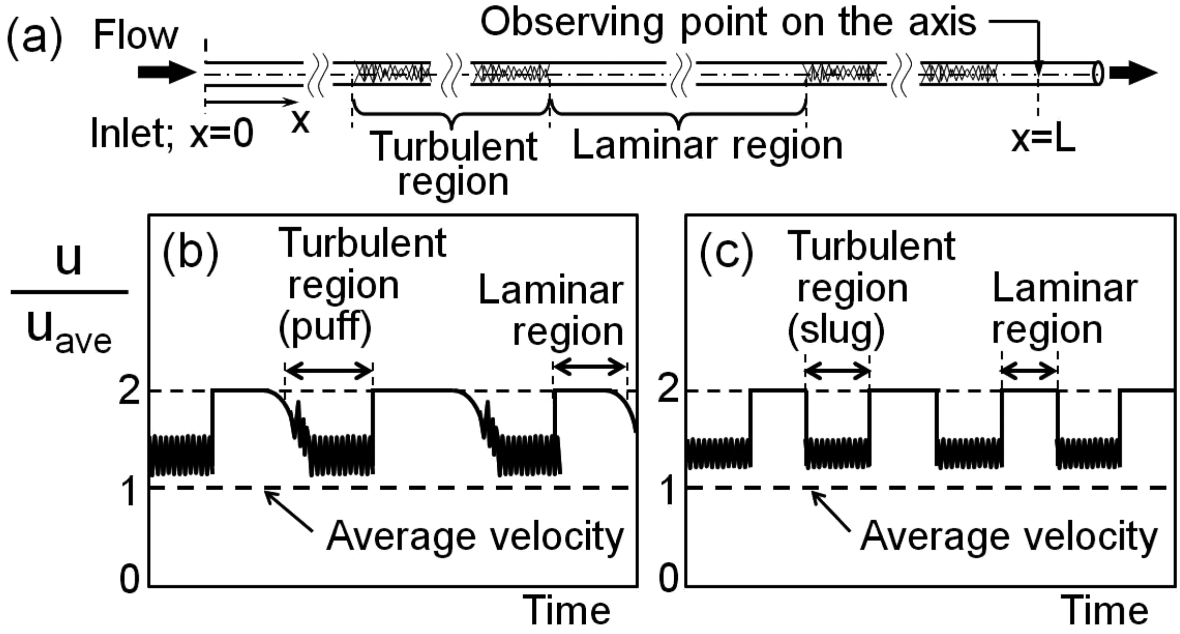

Fig.1 Schematic diagrams. Transitional flow in a circular pipe exhibits intermittency as shown in (a). Turbulent regions called (b) puff and (c) slug are intermittently observed at x=L in velocity signals on the axis. Here, x, u and u_{ave} are the axial distance, axial velocity on the axis and axial average velocity, respectively.

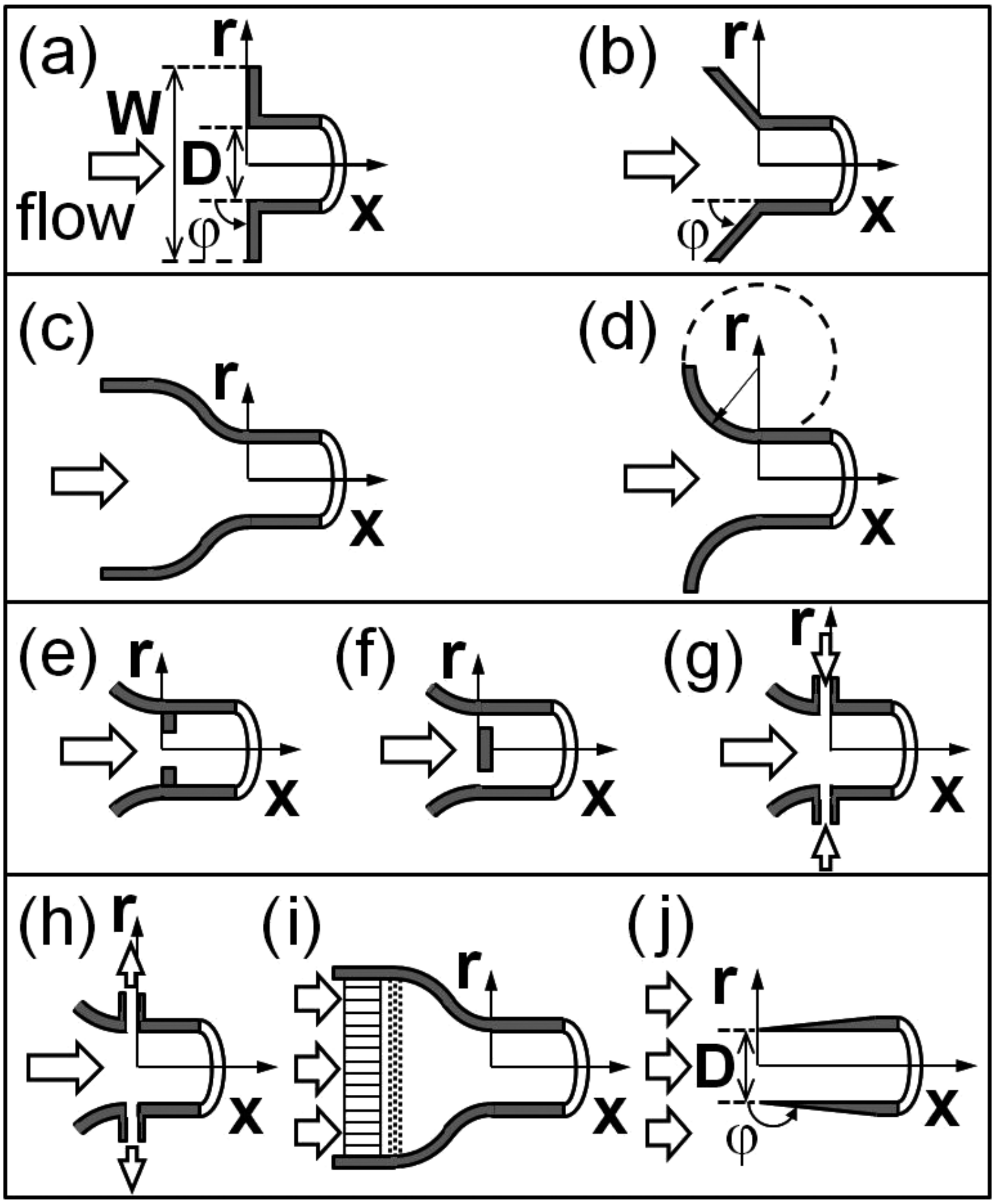

Fig.2 Various components of entrance configuration of circular pipe. Here, x, r, D, W and φ are the axial distance, the radial distance, the inner diameter of a circular pipe, the flange diameter and the angle formed between the flange surface and the x axis, respectively. Abruptly angular contraction types are (a) flange with φ=90 and (b) flange with 0<φ<90, gradually curved contraction types (c) bellmouth and (d) circle, transition promotion devices (e) orifice, (f) disk and (g) jet injection, disturbance suppression devices (h) suction and (i) honeycomb (left) and screen (right) and ideal shape with no separation (j) no contraction with φ=180 (W=D) at x=0.

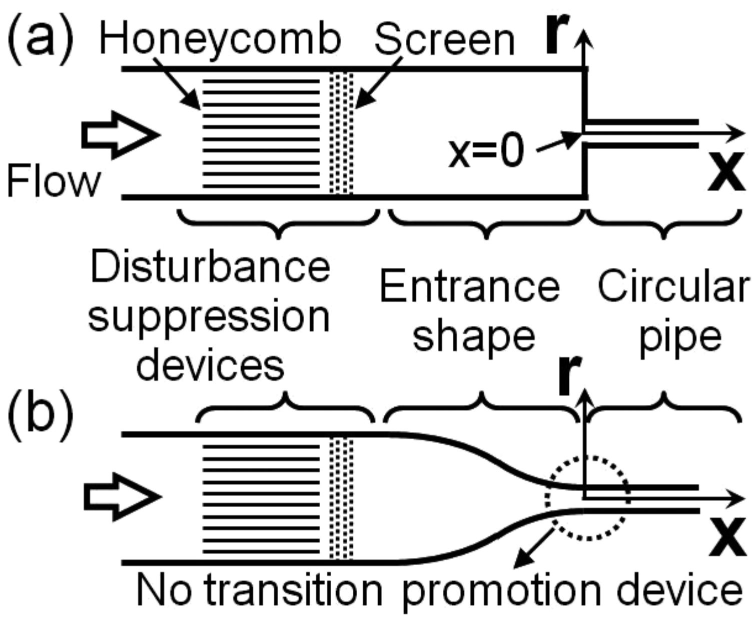

Fig.3 Two entrance configurations with entrance shapes of (a) flange type and (b) bellmouth type. Disturbances at the inlet (x=0) are sufficiently suppressed by honeycomb and screen. No transition promotion device is installed. Does small disturbance at the inlet grow up to the critical finite amplitude disturbance as Reynolds number increases?

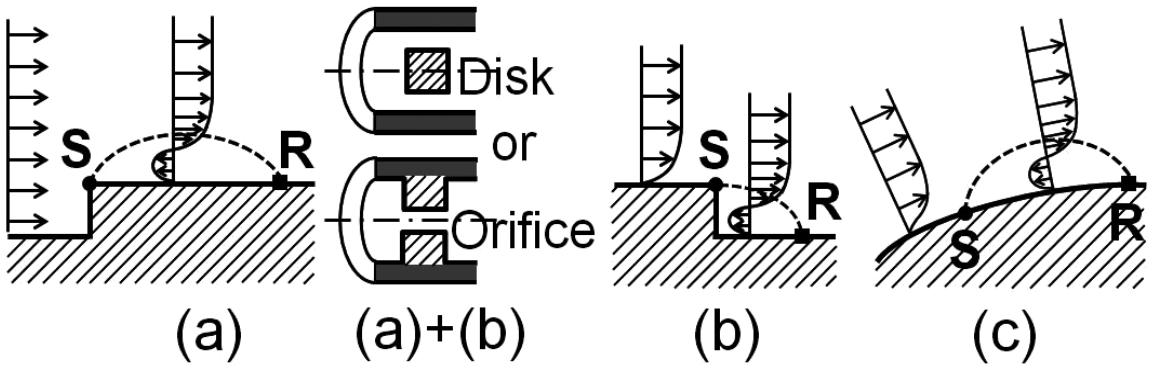

Fig.4 Typical basic shapes causing flow separation in free shear flow. Region of reverse flow is observed in separation bubble denoted by dotted line. The shape combining basic shapes of (a) and (b) forms orifice or disk. Here, S and R are separation and reattachment points, respectively.

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 組立単位	
	名称	記号
面積	平方メートル	m^2
体積	立方メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度[a]，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立方メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率[b]	（数字の）1	1
比透磁率[b]	（数字の）1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン[b]	rad	1[b]	m/m
立体角	ステラジアン[b]	sr[c]	1[b]	m^2/m^2
周波数	ヘルツ[d]	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度[e]	℃		K
光束	ルーメン	lm	cd sr[c]	cd
照度	ルクス	lx	lm/m^2	$m^{-2}\ cd$
放射性核種の放射能[f]	ベクレル[d]	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト[g]	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		$s^{-1}\ mol$

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	$m^{-3}\ s\ A$
表面電荷	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
電束密度，電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（X線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1}\ s\ A$
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}\ mol$

表５．SI 接頭語

乗数	名称	記号	乗数	名称	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60 s
時	h	1 h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10 800) rad
秒	”	1”=(1/60)’=(π/648 000) rad
ヘクタール	ha	1 ha=1 $hm^2=10^4m^2$
リットル	L，l	1 L=1 l=1 $dm^3=10^3cm^3=10^{-3}m^3$
トン	t	1 t=10^3 kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	1 eV=1.602 176 53(14)×10^{-19}J
ダルトン	Da	1 Da=1.660 538 86(28)×10^{-27}kg
統一原子質量単位	u	1 u=1 Da
天文単位	ua	1 ua=1.495 978 706 91(6)×10^{11}m

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	1 bar=0.1MPa=100 kPa=10^5Pa
水銀柱ミリメートル	mmHg	1 mmHg≈133.322Pa
オングストローム	Å	1 Å=0.1nm=100pm=10^{-10}m
海里	M	1 M=1852m
バーン	b	1 b=100$fm^2=(10^{-12}cm)^2=10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デシベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	1 erg=10^{-7} J
ダイン	dyn	1 dyn=10^{-5}N
ポアズ	P	1 P=1 dyn s cm^{-2}=0.1Pa s
ストークス	St	1 St =1$cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}$
スチルブ	sb	1 sb =1cd $cm^{-2}=10^4$cd m^{-2}
フォト	ph	1 ph=1cd sr cm^{-2} =10^4lx
ガル	Gal	1 Gal =1cm $s^{-2}=10^{-2}ms^{-2}$
マクスウエル	Mx	1 Mx = 1G $cm^2=10^{-8}$Wb
ガウス	G	1 G =1Mx cm^{-2} =10^{-4}T
エルステッド[a]	Oe	1 Oe ≙ (10^3/4π)A m^{-1}

(a) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	1 Ci=3.7×10^{10}Bq
レントゲン	R	1 R = 2.58×10^{-4}C/kg
ラド	rad	1 rad=1cGy=10^{-2}Gy
レム	rem	1 rem=1 cSv=10^{-2}Sv
ガンマ	γ	1 γ=1 nT=10^{-9}T
フェルミ		1 フェルミ=1 fm=10^{-15}m
メートル系カラット		1 メートル系カラット= 0.2 g = 2×10^{-4}kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1 cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー），4.184J（「熱化学」カロリー）
ミクロン	µ	1 µ =1µm=10^{-6}m

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