博士学位論文審査要旨

２０２１年1月１9日

論 文 題 目： Three-Dimensional Fluid Flow Structures and Heat Transfer Characteristics of a Backward-Facing Step Flow in a Rectangular Duct
（ダクト内バックステップ流れの三次元流動と熱伝達特性）

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要　　旨：

バックステップを過ぎる流れは，はく離と再付着を伴う最も基礎的な熱流動系として重要であり，これまでにも乱流モデルの開発を主目的とした多くの研究の蓄積がある．しかし，実際の機器で多く見られる流路，すなわち側壁を有するダクト内のバックステップ流れでは，特に低・中速流れ場において流れが三次元性かつ大規模な非定常性を呈すると言われているものの，未だ不明な点が数多く存在しており，この流れ場での熱伝達の詳細と流動現象の解明が求められている．

本論文は，アスペクト比が 16，拡大率が 2 の矩形ダクト内に設けたステップを過ぎる低・中速流れ場を主対象として，局所壁面熱伝達率，再付着位置ならびに三方向速度成分の時間空間分布の計測により，層流から乱流に至る間の壁面熱伝達特性と流れ構造の詳細を明らかにしたものである．

本論文は，第１章から第６章により構成されている．第１章は，バックステップ流れに関する先行研究例を調査し，低レイノルズ数領域（Re=200～1000）における三次元流れと熱伝達の関係が依然として不明であり，その解明が論文の目的であるとしている．第２章は，2D-PIV（二次元粒子画像流速測定法）を用いたスパン方向を含めた局所再付着位置の計測結果から，再付着長さがダクト中央で最大となる一方，側壁近くで最小となること，また，再付着長さがレイノルズ数 Re の増加とともに増大し，400 で最大値をとり，その後減少に転じること，その主因が流路中央から発現する流れの非定常性にあり，それが高 Re 数で側壁に及んでいくことを明示した．加えて，下壁面の対向面側に生じる第二循環領域のはく離，再付着位置の諸特性について明らかにしている．第３章は，感温液晶シートを用いて測定したステップ下壁面および対向壁面の局所熱伝達率分布について，2D-PIV より得た速度分布との関係を明らかにした．下壁面熱伝達率の最大値はいずれの場合も側壁近くに現れ，Re 数によっては二つの極大値を持つこと，その主因が側壁近くに生じる変動を伴う高速流にあることを明示した．対向面側からの強い吹き下ろし流が生む二次流れ，ステップ背後の循環領域内に生じる高速な逆流が下壁面の熱伝達向上に寄与すること，側壁近傍の最大熱伝達率と流路中央の熱伝達率との比が Re 数 400 において最大となること，対向壁面を含めた最大値，中央値，測定領域にわたる空間平均熱伝達率の Re 数に対する変化を示し，対向壁面の平均熱伝達率が下壁のそれより高くなることを見い出した．第４章は，Re 数が 400 の場合に対し，ステレオ 3D-PIV より得た詳細な速度分布と最大熱伝達率との相関から，吹き下ろし流に伴って側壁近傍に周期的に生じる渦運動が高温流体を上方へ持ち上げ，最大熱伝達の発生に寄与していることを明示した．第５章は，ステップ背後の熱伝達不良域解消の一例とし

て，円柱を設置した二次元数値解析結果を示し，流れの非定常化を利用した伝熱促進手法について提案した．第６章は，第１章から５章で得られた事項をまとめると同時に，今後の展望について述べている．

以上，ダクト内バックステップ流れにおける熱伝達と流動構造に関する種々の新たな知見を提供し，熱伝達機構の詳細について解明している．よって，本論文は，博士（工学）（同志社大学）の学位論文として十分な価値を有するものと認められる．

総合試験結果の要旨

２０２１年1月１９日

論 文 題 目： Three-Dimensional Fluid Flow Structures and Heat Transfer Characteristics of a Backward-Facing Step Flow in a Rectangular Duct
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要　　　旨：
本論文提出者は，2017 年 6 月に中国南通大学大学院理工学研究科機械工学専攻博士前期課程を修了後，2018 年 4 月より本学大学院理工学研究科博士課程（後期課程，ISTC（国際科学技術コース））に在学している．

本論文の主たる内容は，International Journal of Refrigeration，International Journal of Science and Engineering Investigations，International Research Journal of Advanced Engineering and Science にそれぞれ１編ずつ，同志社大学ハリス理化学研究報告に１編公表されている．また，アイルランドで開催された国際会議（14^{th} International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics）において Outstanding paper award として表彰されるなど，国内外の学会において十分な評価を得ている．

2021 年 1 月 9 日午後 14 時より約 1 時間半にわたり，提出論文に関する学術講演会（博士論文公聴会）が開かれ，種々の質疑応答が行われたが，提出者の説明により十分な理解が得られた．さらに講演終了後，審査委員により学位論文に関連した諸問題につき口頭試問を実施した結果，いずれも十分な学力を有することが確認できた．

よって，総合試験の結果は合格であると認める．

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氏　　名： 邹 帅

要　　旨：

Flow with separation and reattachment has been encountered in many thermo-fluidic devices. Although it causes energy loss due to pressure drops, it is sometimes intentionally used for heat transfer enhancement. To improve the performance of heat exchangers, understanding the details of such complicated flow and thermal structures is very important. Therefore, attention was paid in this study to a representative typical simple model that can generate separating and reattaching flow called backward-facing step (BFS) flow, the fundamental flow and thermal characteristics of a 3-D BFS flow have been investigated experimentally and a flow modification was also made by numerical simulation aimed to promote the heat transfer enhancement.

In Chapter 1, a review study is proposed to summarize and categorize the BFS related studies in recent years, to provide a general base for comparison and discussions in each aspect and find out some valuable fields that still need to be studied. The basic mechanisms, experimental and numerical topics are reviewed based on a historical viewpoint, while the control methods emerged in recent years are also categorized in this chapter, providing the readers with the latest views of application-related works. Heat transfer effects and related theoretical analysis are also summarized. This chapter firstly describes the basic geometric design, physical and theoretical problems with BFS; and summarizes the experimental and numerical aspects of BFS; In the heat transfer aspect, the representative BFS-based heat transfer designs and combustor studies are discussed; Some representative BFS flow control methods are introduced and summarized; then several emerging topics and future directions are proposed.

In Chapter 2, spatial distributions of flow reattachment position on the bottom wall downstream of a backward-facing step in a duct have been measured by 2D PIV method. Investigations have been done for changing the flow Reynolds number, ranging from steady (*Re*=200) to unsteady (*Re*=1000) flow regimes for the stepped duct having an aspect ratio of 16 and expansion ratio of 2. Non-uniform spanwise distribution of the reattachment length was observed in each case. Within the steady state, the reattachment length shows a unique distribution in the spanwise direction over a channel, that is, having the maximum at the center of the duct but the minimum near the side wall. Generally, the reattachment length increases rapidly as the Reynolds number is increased and has the maximum at the center of the duct at *Re*=400. As the Reynolds number is further increased *Re*>400, the reattachment length conversely decreases due to the flow unsteadiness occurring near the center of the duct. This flow unsteadiness expands to the side wall with the further increase of the Reynolds number, therefore, it makes the spanwise distribution of the flow reattachment position more complicated. The spatial distributions of the reattachment point's existence probability for representative cases (*Re*=200, 400, 600, 800) were studied to further investigate and more clearly clarify the spatial variations of the reattachment phenomena on the bottom wall as time advances. The existence of the side wall restrains the development of the instability from the center of the flow channel

to a certain extent, but high Reyolds number will weaken the influence of the side wall. Time-averaged and instantaneous flow structures were carefully analyzed. The periodicity of the reattachment points, separation points near the side wall and the center of duct was focused on. Periodic instantaneous reattachment points on the bottom wall appears near the duct center for Re=400, the secondary recirculation zone having an obvious periodic movement near the upper wall could be judged by combining the instantaneous separation and reattachment positions near the upper wall.

In Chapter 3, spatial distributions of local heat transfer coefficients on the bottom wall and upper wall downstream of a backward-facing step in a duct flow have been measured by making use of a thermo-sensitive liquid crystal sheet. Heat transfer experiments and three components of the time-averaged velocity measurements by 2D PIV have been done for a wide variety of the flow Reynolds number ranging from Re=400 to Re=900 flow regimes for the stepped duct having an aspect ratio of 16 and expansion ratio of 2. Obtained local Nusselt number changes not only in the streamwise direction but also spanwise direction, that is, the maximum Nusselt number always appears near the side wall region even if the flow Reynolds number is varied. Two Nusselt number peaks appear near the side wall for Re=700, 800, 900, at which the discontinuous reattachment points could be observed near the side wall. Strong downward flow from the step induced along the side wall produces the secondary flow toward the central part of the duct and the area where this secondary flow exists agrees well to the area of the high heat transfer coefficient. High-speed reverse flow from side wall to the duct center can promote the heat transfer on the bottom wall to a certain extent. The flow structure with almost the same velocity magnitude as the reverse flow, but with higher velocity fluctuation downstream the reattachment position near the side wall plays a dominant role in the heat transfer enhancement. When considering the range of 31S downstream of the flow channel, the average Nu value over the entire bottom wall or upper wall can be estimated by averaging that at its center line in the Reynolds number range from 400 to 900. The ratio of Nu_{max} to Nu_{cmax} in different Re on the bottom wall also proves the existence of a three-dimensional feature of this fluid flow model. The three-dimensional flow effect is most obvious at approximately Re=400. The three-dimensional characteristics near the upper wall is stronger than that of the bottom wall in the same Reynolds number condition.

In Chapter 4, the reattachment length data near the side wall and the center of the duct has been collected, the distribution of them once again confirmed the obvious three-dimensional characteristics. Reynolds number of 400 was chosen as the main research object because of its largest reattachment length near the duct center and some critical properties described by other researchers. After analyzing the correlation between the velocity-related parameters and Nusselt number near the bottom wall through Pearson Correlation method, it could be concluded that the velocity magnitude with high fluctuations in the flow direction can directly affect the heat transfer coefficient in this area. Integrating the velocity-related parameters of different cross-sections, the velocity vector of the Stereo PIV and the phase-averaged velocity vectors, the heat transfer enhancement mechanism near the side wall is clarified: A flow near the side wall from the inlet entrance meanders between the circulation zone adjacent to the step and the secondary recirculation zone near the upper wall, as the flow arrives in the region x/S=10 to 12, it turns into a clockwise flow from the upper wall, passing through the side wall and washes downward the bottom wall. In the downstream side, at x/S=14 where the heat transfer is high, a large counterclockwise corner flow which is generated from the upper wall, passing through the bottom wall and side wall and then flows back to the upper wall could be observed above the high heat transfer area. Furthermore, this kind of corner flow has high-speed velocity magnitude and obvious periodicity, making sure that the hot and cold fluid there can be mixed thoroughly and quickly taken away. Thus, the reason for heat transfer enhancement near the side wall at Re=400 was found.

In Chapter 5, an incompressible numerical model for the backward-facing step with an inserted cylinder was established to investigate the effects of various streamwise and cross-stream positions of the cylinder on the flow fields and heat transfer. The heat transfer of the unsteady laminar flow on the bottom wall is significantly enhanced when equipped with a cylinder located at X_C/S=0.6 and Y_C/S=1.0. The overall heat transfer enhancement on the bottom wall exhibited a 114% improvement in the presence of a cylinder and 45% increment in the pressure drop when compared with that of the case with no cylinder. Considering the effect of the periodic instability of the flow, the secondary peak of the time-averaged Nusselt number was observed when X_C/S=0.6 and Y_C/S=1.0. This occurred when the hot fluid was pumped from the bottom wall to the main flow region and the cold fluid was entrained from the main flow region to the proximal of the bottom wall.

In Chapter 6, the findings obtained in this research were summarized and the prospects for future BFS-related were pointed out.