A numerical study on the irregular roughness effects in compressible natural convection flow

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論文内容の要旨

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論文題目（外国語の場合は，その和訳を併記すること。）

A numerical study on the irregular roughness effects in compressible natural convection flow

圧縮性自然対流における不規則粗度の影響に関する数値解析

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（注）2，000 字～4，000 字でまとめること。

The phenomena of natural convection are common in modern industry and our daily life, and many cases of natural convection are taking place under a high temperature difference condition. Thus, the compressibility of the working fluid is necessary to be considered. On the other hand, the topology of solid surface has direct and significant influence on the natural convection nearby, different deterministic surfaces have been studies widely (Yousaf M, 2015; Jiang H, 2019; Mohebbi R, 2019). But by taking the reality into account, the 3D irregular roughness is more general on solid surface, such as asphalt road, granite, and corundum surfaces (Persson B N J, 2004). Thus, in current study, natural convection flows in enclosures with irregular roughness on both vertical sidewalls have been studied numerically considering the compressibility of the working fluid.

The thermal convection widely exists in the applications where the fluid are involved in the heat transfer, such as power generators and turbines, and according to the driven forces of the fluid, convective heat transfer is further divided into forced convection, natural convection and combined-convection (Barhaghi D G, 2007). In this study, the major concern is natural convection where the buoyancy force plays a role as the driving force of the fluid flow. The generation of buoyancy originates from the inhomogeneous density of the fluid, i.e. the fluid motion is not driven by any external force (Ozisik M N, 1985). The denser or heavier particles of fluid will be pulled by the gravity more strongly than the lighter particles, thus the relative motion inside the fluid will occur, and as the carrier of the energy and mass, convection of the fluid will bring the delivery of the energy. Since no external source is required, natural convection can be found in small-scale to large-scale industrial applications. Thus, a better understanding of natural convection will lead to improving efficiency and saving energy.

From the mechanism of natural convection, one of the vital issues which all researchers should pay attention to is the change in the fluid density because of the change in temperature and the heat transfer. In order to deal with this issue, the Boussinesq approximation has been proposed. According to this approximation, the variation of the fluid density will only be considered when it is multiplied by the gravitational acceleration in the body force term of the momentum equations, and the fluctuations of density in the motion of the fluid are principally treated as the results from the heat transfer (Spiegel E A, 1960). Gray and Giorgini (1976) assessed the validity of this approximation for liquids and gases, and pointed out that for the Rayleigh-Bénard problems, when the working fluid is air, the temperature difference should be smaller than 28.6K. For the flows in an enclosure cavity with 2 vertical heated sidewalls, when the temperature difference ratio $\epsilon = (T_H - T_C)/T_C$ is more than 0.1, the Boussinesq approximation might not be accurate (Zhong Z Y, 1985). Paillere et al. (2000) found large temperature difference will result in the non-symmetrical distribution of the heat transfer and the flow patterns. Talukdar et al (2018) also observed the anti-symmetry in the patterns of buoyancy-driven laminar flows in the square cavities, and the emergence of this anti-symmetry was attributed to the temperature-dependent fluid properties. There is no doubt that the Boussinesq approximation can be very convenient for incompressible solvers to handle the problems which involve the fluctuations of the fluid density, but the limitations of this approximation deserve thoughtful consideration.

Thus, in current research, a compressible solver without Boussinesq approximation has been adopted to deal with natural convection problems. However, the magnitude of fluid velocity due to the buoyancy force is generally smaller than the speed of sound by several orders of magnitude. Therefore, a preconditioning method (Weiss, 1995) is adopted to resolve the governing equations. Combined with the Roe scheme (Roe P L, 1981) and dual time-stepping method (Venkateswaran S, 1995), an implicit solver has been developed based on the lower-upper symmetric Gauss-Seidel (LUSGS) schemes, shown in Chapter 2.

In most of the previous researches, the thin sheet, rectangular or sinusoidal were chosen as the shapes of roughness or partition. Xu et al. (2009) installed a thin fin on the hot sidewall of a differentially heated cavity, and investigated the effects of this fin on the flow field. At the *Ra* of 2.29×10^8, and behind the fin, the intermittent plume of the fluid will be generated due to the existence of the adverse temperature gradient in this region. Yousaf (2015) used the Lattice Boltzmann method to study the influence of the sinusoidal roughness elements on vertical sidewalls on the heat transfer in a two-dimensional square cavity. They found that, under a condition of laminar flow ($Ra = 10^3$ to 10^6), as the number and size of roughness elements increase, the heat transfer performance decreases. At the same time, some eddies were observed in the interstice between two roughness elements at $Ra = 10^4$, but disappeared in the case of 10^6.

Differently, in this study, the surface roughness is irregular and random to fit the reality. To describe this type of roughness, the parameters should include the height of the roughness element, the probability density of the roughness element's height, and the change frequency of the roughness elements and other necessary parameters, thus the power spectral density (*PSD*) (M.M. Kanafi, 2017; Y. Xian, 2019) is an easy and efficient way to combine the structural information of the roughness in both vertical and lateral directions. *PSD* is defined as the Fourier transform of the autocorrelation function of roughness element heights (Nayak P R, 1971). Thus, we can get height information after inverse Fourier transform of *PSD*. The detailed introduction can be found in Chapter 3.

In Chapter 4, the natural convection in a cavity with 3D irregular roughness elements on sidewalls has been investigated at the Rayleigh number of 10^6, using a compressible solver. The roughness was generated through a given power spectrum density with the roll-off wavenumber equal to 10^3 m^{-1} and the temperature difference between two sidewalls was 50K. The results of thermal fields in the cavities showed that the peaks on the rough surface will decrease the thickness of the thermal boundary layer but the valleys will increase it in the upstream region. However, in the downstream region, the thickness of the thermal boundary layer is thick enough that this effect is no longer obvious. Near the hot sidewall, the peaks will accelerate the flow field slightly, but the valleys will give a conspicuous deceleration to the flow field, and this phenomenon exists in both upstream and downstream regions. On the other hand, the fluid will bypass the elements in 3D simulation instead of getting trapped between two roughness elements.

After Chapter 4, the numerical methods we adopted have been proved effective to deal with the natural convection problems in the enclosure with irregular rough sidewalls. Then, the influence of different irregular rough surfaces on heat transfer was investigated in Chapter 5. By changing the roll-off wavenumber, 4 different irregular rough surfaces were generated. An accurate method to measure the temperature gradient on the complex surface was applied and the results showed that as the q_R^* increases the average *Nu* on the surfaces decreases under the condition of $Ra = 10^6$. Another notable phenomenon is that large q_R^* indicated the denser distribution of the roughness elements with short wavelengths, then these roughness peaks were able to amplify the maximums of local *Nu*, but meanwhile, the space among the roughness elements would be separated into small pieces by these roughness peaks and valleys. After dividing the average Nu into top average Nu and bottom average Nu, the results showed that the bottom average Nu was more sensitive to the change of q_R^* than the top average Nu, and as q_R^* increased, the bottom average Nu had a conspicuous tendency to decrease.

The turbulent natural convection flows have been investigated based on DNS in Chapter 6. The fluid was considered as compressible and enclosed in a cuboid cavity with 3D irregular roughness elements on its sidewalls at a Rayleigh number of 1×10^{10}. The irregular roughness with q_R^* of

32 was same as in Chapter 5. The probability density functions (*PDF*) of the temperatures and velocities at the monitor probes were measured and the profiles of *PDF* show the flows in the downstream regions had the features of turbulence and the roughness increased the fluctuations of the flows nearby. In the local areas, the roughness peak accelerated the fluid nearby, and then the local convection increased, but the roughness valley had an opposite effect on the fluid. Thus the distributions of local Nusselt numbers have a high value in the vicinity of roughness peaks but the low in valley regions. From the average *Nu* on the hot sidewall, the rough case is lower than the smooth case by nearly 8%. But results of eddy heat flux (*EHF*) indicated that the heat transfer generated by the turbulence near the rough surface was much higher than the smooth case, and compared with the smooth case, conspicuous *EHF* could be found from a more upstream area near the rough sidewalls. From the isosurfaces of Q-criterion near both rough and smooth sidewall, we noted that the roughness was able to increase the vorticity and change the structures of the fluid nearby, but the vortices only appeared in the local areas of roughness peaks, and the fluid in valley areas kept a very low rotation rate. Although the roughness reduced the surface heat transfer, as the *Ra* increases, the difference of average Nusselt numbers between smooth and rough cases will be diminished, and the mixing effects of turbulence played an important role in this tendency.

The current study clarified the effects of isotropic irregular roughness on the compressible natural convection flows in enclosed cavities under both laminar and turbulent conditions without Boussinesq assumption. Meanwhile, the flow structures near the rough surfaces were represented in detail. The results of this dissertation can provide a reference for the design of engineering applications involving high-temperature problems.

（別紙１）　　　　　　　　　　　　論文審査の結果の要旨

氏名	任 淳麒（REN BOQI）
論文題目	A numerical study on the irregular roughness effects in compressible natural convection flow 圧縮性自然対流における不規則粗度の影響に関する数値解析

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要　旨

本論文では、垂直に立てられた壁面を加熱することよって生じる浮力で駆動される自然対流を対象として、特に壁面が粗度を有する場合に、個体壁から流体への熱輸送に与える影響について数値解析を用いて調査し、その物理メカニズムを解明したものである。ここでは粗度を自然界や工業製品にみられるようなよりランダムな配置として捉え、空間的な粗さの分布をパワースペクトル密度として表現することでパラメータ化して粗面を再現している点と、ブシネスク近似が適用できないような高熱源を扱えるように圧縮性流体解析を行っていることに特長がある。

第１章で研究の背景と目的、第２章で用いた数値解析手法を述べた後、第３章では壁面上の不規則粗度の生成方法について述べている。
第４章では、第２章と３章で述べた手法を立方体形状の内部流に適用し、垂直に正対する２面をそれぞれ加熱、冷却することで駆動される層流自然対流を対象として、粗面が熱伝達に与える影響とそのメカニズムを滑面と比較することで調べている。この結果、壁面での平均ヌッセルト数は粗面と滑面で大きな差異は見られないが、壁面上の局所的なヌッセルト数は粗面と滑面では大きくことなることを示し、粗面を大きく山と谷に分類してそれぞれの周りの流れと熱輸送の関係を詳細に調査し、そのメカニズムを解明している。
第５章では、壁面粗度の特徴をその空間分布のパワースペクトル密度上でパラメータ化し、ここではスペクトルが減衰する境界波数をロールオフ波数として表現し、４種類の粗面を作成することで、粗度の特性の違いが自然対流の熱輸送に与える影響について調べている。その結果、層流境界層においては、ロールオフ波数が増加するに従い、壁面の平均ヌッセルト数が減少することを発見している。また局所的には粗面の山側での熱伝達の増加はロールオフ波数に大きく影響しない一方、谷側は大きく依存することを明らかにしている。
第６章では、壁面境界層が層流から乱流に遷移するレイリー数を対象として、粗面が壁面での熱伝達に与える影響を調べている。確率密度関数を用いて加熱垂直壁面の下流側で流れが層流から乱流へ遷移していることを確認した上で、滑面と比較して粗面の場合は流速や温度の変動がより大きくなっていることを明らかにしている。また、壁面での平均ヌッセルト数で壁面熱伝達を評価した場合、滑面と比較して粗面では 8%程度の低下が見られる一方、乱れ（渦）による熱輸送は滑面と比較して増大していることを明らかにしている。一方、壁面上を局所的に見た場合、層流の場合と同様に熱伝達は粗面の配置に大きく依存し、山と谷では熱伝達に対して正反対の効果が表れる結果、局所ヌッセルト数の最大値と最小値は滑面と比較してより大きく変動することを示している。また、レイリー数に対する依存性を調べた結果、レイリー数が増加するに従って滑面と粗面のヌッセルト数の差は小さくなり、乱流による熱輸送の増加がより支配的となる傾向があることを明らかにしている。

以上のように、本論文では流体力学、熱力学とその応用として機械工学に対して、新たな重要な知見を得たものとして価値ある集積と認められる。また、内容については現在、２本の学術論文と１本の国際会議に既に発表済みである。提出された論文はシステム情報学研究科学位論文評価基準を満たしており、学位申請者の任 淳麒（REN BOQI）は、博士（工学）の学位を得る資格があると認める。