様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）An investigation of the self-transition to turbulence by buoyancy force using compressible direct numerical simulation

研究課題名（英文）An investigation of the self-transition to turbulence by buoyancy force using compressible direct numerical simulation

研究代表者

ＬＩ　ＣＨＵＮＧＧＡＮＧ（Li, ChungGang）

神戸大学・システム情報学研究科・講師

研究者番号：７０６５０６３８

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研究成果の概要（和文）：本研究では、垂直チャネルの高温と低温壁面の間に、自然対流が誘導された流体の不安定現象を調べる。高精度の熱流体を解析するため、浮力からの生成された乱流を適用できる圧縮性ソルバーを発展した、従来より高精度な結果を得られる。シミュレーションの結果より、自然対流に関する既存の法則をここでは適用できないことを示している。以上の課題を解決するため、もとは水平自然対流の現象を解明するための提唱されたGrossmann-Lohse法則を使い、不安定現象を解明し、乱流と層流を共存する流れ場を示す。更に、以上の結果を活用し、粗面と乱流の相互作用に影響された自然対流の現象を解明している。

研究成果の学術的意義や社会的意義
垂直チャネルの高温と低温壁面についての設置は様々な日常生活の応用がある。例えば、壁掛け式パネルヒーター。計算と数値方法の制限のため、このような研究はまだされていないである。以上の課題を解決するため、高精度な計算方法を開発し、シミュレーションをした。この結果より、従来の法則を適用できないことが示す。さらに、新しい不安定的な熱流体の相互作用現象を解明する。未来に、ヒーターとエネルギー節約に関する課題を貢献することを期待される。

研究成果の概要（英文）：The unstable phenomena induced by the natural convection in an open-ended vertical channel with hot-cold wall configuration are investigated. To accurately perform the simulation, a modified compressible solver, which can deal with the buoyancy-induced turbulence, has been developed. The solver can appropriately control the dissipation as an implicit turbulence model to have a more accurate result. The simulation result shows that the existing empirical experience for the natural convection in a vertical channel cannot be applied here. To better reflect the underlying physics, Grossmann-Lohse theory, originally proposed of horizontal (Rayleigh-Benard) convection, is applied to describe the flow field and the scale analysis for the flow characteristics near the wall is also performed. The coexisted flow field of the laminar and turbulence are observed. The above research result has been applied for the simulation of the natural convection with 3D random roughness elements.

研究分野：熱流体解析

キーワード：unstable phenomena　natural convection　turbulence

様　式　C－１９、F－１９－１、Z－１９（共通）

１．研究開始当初の背景

The transition (unstable phenomena) in natural convection is a critical phenomenon encountered in diverse engineering applications, such as solar energy collection, chimney design, and the thermal analysis of fins. However, the simulations of transition to turbulence always start from a perturbative inlet or initial condition. As a result of that, the transition is more or less parameter dependent. Besides, concerning engineering applications, the temperature differences responsible for variations in density in natural convection always exceed the limits regarding the validity of the incompressible solver with the Boussinesq approximation (30 K) [1]. From above, it is known that the self-transition to turbulence by buoyancy force under the practical conditions (temperature difference larger than 30K) has not been studied yet.

２．研究の目的

(1) A modified compressible solver which can deal with the buoyancy-induced turbulence with larger temperature differences was developed. With this solver, a more accurate result can be obtained, and using direct numerical simulation (DNS) to investigate the transition in natural convection becomes feasible.

(2) The unstable phenomena induced by the natural convection in an open-ended vertical channel with hot-cold wall configuration are investigated. With this setting, the artificial perturbations to generate turbulence can be abandoned. Therefore, the parameter independent simulation is toward and the result can be the benchmark to optimize turbulence models.

３．研究の方法

To investigate the transition in natural convection with larger temperature differences, the solver suitable for the current simulation was proposed first. And then, this solver was adopted to perform the simulation to obtain accurate results. Finally, the flow field was investigated to understand the mechanism.

(1) A modified compressible solver which can deal with the buoyancy-induced turbulence with larger temperature differences was developed. In this solver, an all speed preconditioned Roe (APRoe) [2] is adopted to appropriately treat flows at extremely low speed regions. And then, a reconstruction method for the MUSCL scheme at low Mach numbers (M5LM) [3] is applied to attenuate the dissipation. Under the situation of the finer resolution, the dissipation can be reduced to have a more accurate result such as performing DNS. On the other hand, under the situation of the coarser resolution, the numerical dissipation of the compressible solver is utilized as a subgrid scale (SGS) model for the implicit large eddy simulation (LES).

(2) To well conditionally assign the boundary conditions at inlet and outlet, the compressible solver combining absorbing and non-reflecting boundary conditions for extremely low Mach numbers is applied to eliminate the problem of requiring a priori knowledge of the flow rate. Besides, to better reflect the underlying physics, the turbulent behavior near the wall is investigated and following Ng et al.[4], the Grossmann-Lohse (GL) theory, originally proposed for the horizontal convection (Rayleigh-Benard), is applied to investigate the flow and temperature fields to better understand physics.

４．研究成果

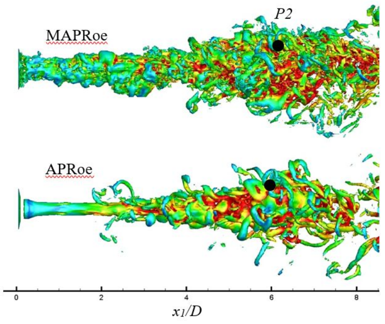

Fig.1 Comparison of the vorticity isosurface

(1) The thermal plume was adopted to validate the current solver (MAPRoe). Fig. 1 shows the vorticity iso-surface contoured using the velocity magnitude. The transition occurs after $x_1>D$ and the hairpin-shaped structures mainly form in the vortex regions when $x_1>4D$. This observation is basically consistent with that in [5]. Overall, the buoyancy-induced evolution from laminar to turbulence can be clearly observed using the MAPRoe.

The comparison the development of the vorticity isosurface contoured using the velocity magnitude between MAPRoe and APRoe are also shown. In the laminar region of $x_1 < 2D$, for the MAPRoe model, the unsteady concentration of vorticity develops and gradually enlarges up to x_1 = 2D, which is basically consistent with the description in [6]. Meanwhile, for APRoe, the unsteady phenomenon only occurs around *x₁* = 2D. Additionally, according to DNS results [6], the transition from laminar flow to turbulence is located close to *x₁* = 3D. This phenomenon is more obvious for MAPRoe than for APRoe. In the turbulence region of *x₁* > 4D, hairpin vertical structures dominate the flow field and interlace with each other [6] and MAPRoe captures this phenomenon more completely than does APRoe. Overall, the development of the flow field from laminar flow to turbulence is captured much more completely by MAPRoe than by APRoe.

(2) The temporal power spectrum of the temperature fluctuation against Strouhal number ($St = f \times D / U_0$) is obtained for *P2*. The result of MAPRoe presents a different distribution near the LES cut-off frequency. Moreover, the −5/3 Kolmogorov power law decays more rapidly, following instead a −3 power decay law. This rapid decay is caused by the buoyancy force in the inertial-convective region, and it has been proposed as a result of numerical simulations [5] and experimental observations by Dai and co-workers [7]. As shown in Fig. 2, in P2, the over-dissipation in APRoe enlarges the turbulent structure. Hence, the fluctuations based on time in APRoe will be overestimated owing to the production of the unphysically larger structure. The overestimated fluctuations cause the accumulation of energy at smaller scales. Meanwhile, the current solver can provide appropriate dissipation to correctly transfer energy from large to small scales. The result demonstrates that the MAPRoe captures the turbulence energy transfer induced by the buoyancy force.

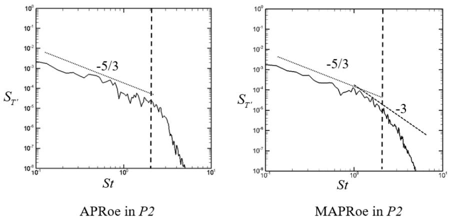

Fig. 2 Temporal power spectra of temperature fluctuations

From (1) and (2), it can be known that the current solver can be applied for the transition in natural convection with high temperature differences.

(3) The natural convection in a vertical channel as shown in Fig. 3 is investigated and the Rayleigh number based on the height of the channel is 5.4×10^5. Two different cases are conducted. One is that the wall temperatures in the left and right are $T_c = T_0$ and $T_h = T_0 + 45K$, respectively. The other is that the wall temperatures in the left and right are $T_c = T_0 - 15K$ and $T_h = T_0 + 30K$, respectively. Please note here. The temperature differences between two walls for these two cases are the same so that the Rayleigh numbers are also identical.

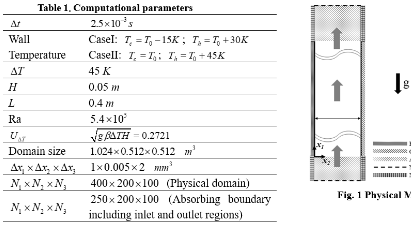

Table 1. Computational parameters

Δt	$2.5 \times 10^{-3}\ s$
Wall Temperature	CaseI: $T_c = T_0 - 15K$; $T_h = T_0 + 30K$ CaseII: $T_c = T_0$; $T_h = T_0 + 45K$
ΔT	$45\ K$
H	$0.05\ m$
L	$0.4\ m$
Ra	5.4×10^5
$U_{\Delta T}$	$\sqrt{g \beta \Delta T H} = 0.2721$
Domain size	$1.024 \times 0.512 \times 0.512\ \ m^3$
$\Delta x_1 \times \Delta x_2 \times \Delta x_3$	$1 \times 0.005 \times 2\ \ mm^3$
$N_1 \times N_2 \times N_3$	$400 \times 200 \times 100$ (Physical domain)
$N_1 \times N_2 \times N_3$	$250 \times 200 \times 100$ (Absorbing boundary including inlet and outlet regions)

Fig. 3 Vertical channel with hot-cold wall

Fig 4. shows the contour of the instantaneous temperature and the instantaneous velocity for both CaseI and CaseII. For the CaseII, except the region near the outlet, the flow filed and the temperature filed is almost stationary. On the other hand, CaseI shows slightly unstable phenomena. Generally speaking, at this moderate Rayleigh, the natural convection in a vertical channel should be stationary such as shown in CaseII. Therefore, it is obvious that the existing empirical experience for the vertical channel flow can't be applied to Case I.

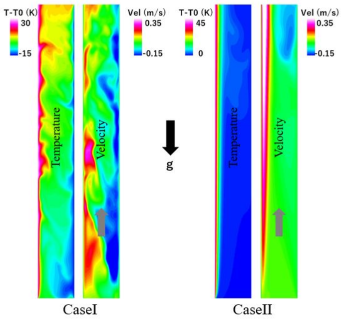

Fig. 4 The instantaneous temperature and velocity

(4) To investigate the unstable phenomena in CaseI, the natural convection in an enclosure with aspect ratio 1/8 (*H/L*) at the same Ra Number, 5.4×10^5, in [4] is compared. In Fig. 5, the statistical data at *x₁=0.2m* are compared with the DNS result. Please note here. The discrepancy especially near the center of the channel height, $x_2 / H = 0.5$, is caused by the different conditions of the temperature on the wall. In [4], the condition of $T_H = T_0 + 1/2 \times \Delta T$ and $T_c = T_0 - 1/2 \times \Delta T$ is assigned. On the other hand, in CaseII, the condition of $T_H = T_0 + 2/3 \times \Delta T$ and $T_c = T_0 - 1/3 \times \Delta T$ is assigned. However, the qualitatively good agreement with the DNS results

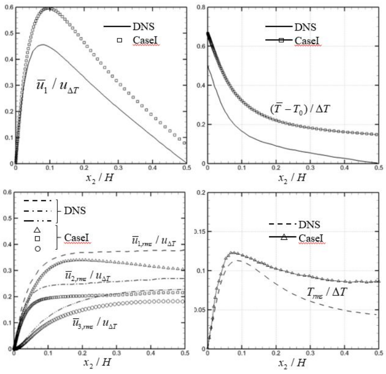

Fig. 5 Statistical data

implies that the physical phenomena are closer to those in an enclosure rather than in a vertical channel with an only one-side heated wall.

(5) To study the flow and thermal fields near the wall, the boundary-layer behavior is investigated. Following [4], for the hot wall, the kinetic boundary-layer thickness δ_u is calculated by intercepting $\bar{u} = x_2 \times d\bar{u} / dx_2$ and $\bar{u} = \bar{u}_{\max}$. Similarly, the thermal boundary-layer thickness δ_T is calculated by intercepting $\bar{T} = T_h + x_2 \times d\bar{T} / dx_2$ and $\bar{T} = T_h - \Delta T / 2$. Through these calculations, the effects on the flow can be clearly separated. One is from the boundary layer due to the velocity gradient, $d\bar{u} / dx_2$ and the other is from the bulk region caused by the bulk velocity, $\bar{u} = \bar{u}_{\max}$. These distributions are compared with the kinetic dissipation and the thermal dissipation in Fig. 6. to better understand the physical insight. The kinetic dissipation due to the mean velocity, $\overline{\varepsilon}_{\bar{u}} = \mu(\mathrm{d}\bar{u}_2 / \mathrm{d}x_2)$ and due to the velocity fluctuations $\overline{\varepsilon}_{u'} = \mu(\partial u_i' / \partial x_j)^2$, and the thermal dissipation due to the mean temperature, $\overline{\varepsilon}_{\bar{T}} = k(\mathrm{d}\bar{T} / \mathrm{d}x_2)$ and due to the temperature fluctuations, $\overline{\varepsilon}_{T'} = k(\partial T' / \partial x_j)^2$ are shown. Based on the results, inside the boundary layer, the physical properties of the mean dominate the flow field. On the other hand, outside the boundary layer, the physical properties of the fluctuation dominate the flow field. It is consistent with the GL theory. Because away from the wall, the turbulence due to the natural convection is not strong enough to generate the boundary layer, GL theory decomposes the kinetic dissipation into the boundary layer and bulk contribution. According to (3), (4) and (5), it can be known that instead of the existing empirical experience for the vertical channel flow, the current flow field is closer to that in an enclosure. Moreover, according to the distribution of the kinetic dissipation and thermal dissipation, it is found that both laminar and turbulent behaviors are coexisted. Therefore, the GL theory is applied to explain the reason for the coexistence.

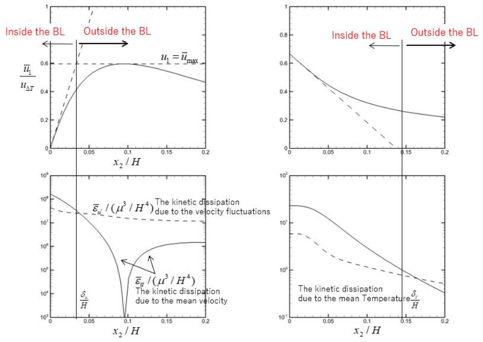

Fig. 6 The boundary layer behavior

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５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　0件／うちオープンアクセス　0件）

１．著者名 Li Chung-Gang	４．巻 117
２．論文標題 A compressible solver for the laminar?turbulent transition in natural convection with high temperature differences using implicit large eddy simulation	５．発行年 2020年
３．雑誌名 International Communications in Heat and Mass Transfer	６．最初と最後の頁 104721～104721
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.icheatmasstransfer.2020.104721	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Ren Boqi、Li Chung-Gang、Tsubokura Makoto	４．巻 173
２．論文標題 Laminar natural convection in a square cavity with 3D random roughness elements considering the compressibility of the fluid	５．発行年 2021年
３．雑誌名 International Journal of Heat and Mass Transfer	６．最初と最後の頁 121248～121248
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ijheatmasstransfer.2021.121248	査読の有無 有
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〔学会発表〕　計1件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 ChungGang Li, Makoto Tsubokura
２．発表標題 UNSTABLE PHENOMENA OF VERTICAL NATURAL CONVECTION IN AN OPEN-ENDED CHANNEL WITH HOT-COLD WALL CONFIGURATION
３．学会等名 13th International ERCOFTAC Symposium on Engineering Turbulence Modelling and Measurements (ETMM13)（国際学会）
４．発表年 2019年～2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関