Computer Life (CPL) ISSN: 1819-4818
DELIVERING QUALITY SCIENCE TO THE WORLD

Numerical Analysis of the Transition from Heat Conduction to Convection in Annulus Enclosure

Kunfeng Sun

School of Energy & Environment, Zhongyuan University of Technology, Zhengzhou, China

---

Abstract: In this paper, OpenFOAM is used to simulate the annulus enclosure at low Gr number, and the temperature field is obtained. The critical transition value from heat conduction to natural convection are summarized. The method of judging critical number Grc is put forward. First, compared with the pure thermal analysis solution, if the relative error is less than a certain value, it will be used as the basis for determining pure heat conduction. Second, under the same condition, the boundary conditions of the inner and outer walls are interchanged, and the calculated results are consistent. According to the criterion, when Gr is no more than 2500, the calculation error is about 1%, and when Gr=1000 is taken as the criterion, the calculation error is only 0.2%. The numerical results show that the pure heat conduction problem is not related to the internal and external wall conditions, which is consistent with the theoretical analysis, and also shows the correctness of OpenFOAM calculation.
Keywords: Annulus Enclosure, Natural Convection, Heat Conduction, OpenFOAM.

---

1. INTRODUCTION

Natural convection in horizontal concentric annulus is a research topic of many scholars. There are many natural convection problems in industrial production, such as cold water flow in storage tank of cool storage air-conditioning, cooling of electronic equipment, building ventilation and other fields. The book [1-3] indicates that the flow in the enclosed spaces mainly depends on the Gr number of the characteristic value of the gap thickness. The the critical number of heat conduction to natural convection in a vertical enclosed is given in [1,2], where $Gr_\delta < 2000$, In [3] the critical number is $Gr_\delta < 2860$.Xufeng et al. [5] studied the natural convection in the side heating cavity by experimental and numerical methods. It is pointed out that when Ra < 1000, there is no clear stratification in the side heating cavity fluid and the isotherm of the core area is approximately vertical distribution. The temperature of the fluid in the cavity meets the Laplace equation, and the heat transfer is mainly controlled by heat conduction.

Peng LAN et al. [6] used FVM [4] to simulate the natural convection of cold water in horizontal annular gap. Jiang Changjian et al. [7] simulated the laminar natural convection in horizontal concentric tube, and calculated the constant heat flux and wall temperature in the range of different Ra number and radius ratio. Zou Jianfeng et al. [8] calculated the laminar natural convection in the square cavity of circular tube with different diameter by numerical method. Dong Qing [9] et al.

Studied the natural convection heat transfer between water and horizontal micro cylinder surface with different sizes by experimental method. [10-12] studied the natural convection of cold water under ice storage.

The above literature does not give the critical value of concentric annular enclosure. In this paper, on the basis of previous studies, OpenFOAM is used to analyze the critical value of the transition from heat conduction to natural convection in a concentric annular enclosure.

2. PROBLEM DESCRIPTION

The geometry of the present two-dimensional problem is shown in Fig.1, The outer wall is maintained at constant temperature To, the inner wall is maintained at constant temperature Ti .

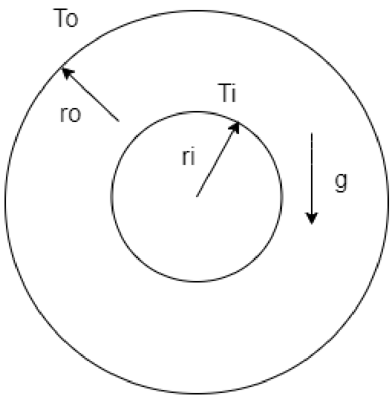

Fig. 1 Geometry and the boundary condtions

The boundary conditions for the present problem as shown in Fig. 1 are as follows:

u==0,T=T_i; on the inner wall R=r_i

u = v =0, T=T_o on the inner wall R=r_o

3. MATHEMATICAL MODELING AND NUMERICAL PROCEDURE

3.1 Governing equations

In this work, the flow is considered to be steady, two-dimensional, incompressible and laminar. The maximum temperature difference is assumed to be small enough to justify the use of the Boussinesq approximation, and the continuity, momentum, and energy equations governing the flow and heat transfer are given as follow:

Continuity Equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

Momentum Equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2})+g\beta(T-T_{ref}) \tag{3}$$

Energy Equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=a(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}) \tag{4}$$

Where Ra and Gr number and gap defined as follow:

$$Ra = \frac{g\beta(T_i - T_o)\delta^3}{va} \quad (5)$$

$$Gr = \frac{g\beta(T_i - T_o)\delta^3}{v^2} \quad (6)$$

$$\delta = r_o - r_i \quad (7)$$

3.2 Computing Tools and method

OpenFOAM is an open source CFD software [13-15]. It is an open source, highly extensible and reliable free software. It is developed and designed based on C++ language, including a series of preprocessing tools, partial differential equation solver and post-processing tools. It is also the most widely used CFD open-source software. It includes a wealth of physical solvers, such as Laplace equation, incompressible N-S equation solver, a variety of turbulence solver, multiphase flow solver and so on. This paper uses buoyantBoussinesqsimplefoam solver in OpenFOAM 5. X, and the SIMPLE algorithm was used for the pressure–velocity coupling scheme in the solver,and with relaxation factors of 0.3 for pressure, 0.7 for momentum and 0.5 for T.

In order to reduce the influence of irrelevant factors in the numerical calculation of closed concentric annulus, the calculation is mainly carried out under small temperature difference. In this case, the incompressible fluid approximation and Boussinesq assumption can be used. Because it is laminar flow calculation, half of the physical model is chosen as the calculation domain, which can greatly improve the calculation speed. Meanwhile, the maximum temperature difference is assumed to be small enough to satisfy the Boussinesq approximation.

The fluid uses air as the flow medium, and its physical properties are shown in the Table.1 below. The acceleration of gravity is -9.81m/s^2

Table 1 Thermophysical properties of fluid

	k $(W/(m \cdot K)$	$\beta \times 10^5 (K^{-1})$	$v(m^2/s)$	Pr
air	0.0242	3e-3	1e-5	0.7

Firstly, three kinds of annulus radii and different wall temperature modes are used to calculate. The number of Gr varies from 600 to 5000. For the convenience of comparison, we take Gr as the evaluation benchmark.

4. RESULTS AND DISCUSSION

4.1 Temperature distribution

In the present study, natural convection heat transfer of fluid in an annulus is investigated. The temperature distribution under various working conditions is obtained, as shown in Fig.2 below. It clearly shows the temperature field that at low Gr, and the temperature lines are even and parallel, and the isotherms are almost concentric circles. With the increase of Gr number, the isotherms begin to twist. But near the inner and outer ring wall, the heat conduction is still dominant. And the results are obtained in different Gr ‘s, the calculation shows conduction is the dominated mechanism in low Gr.

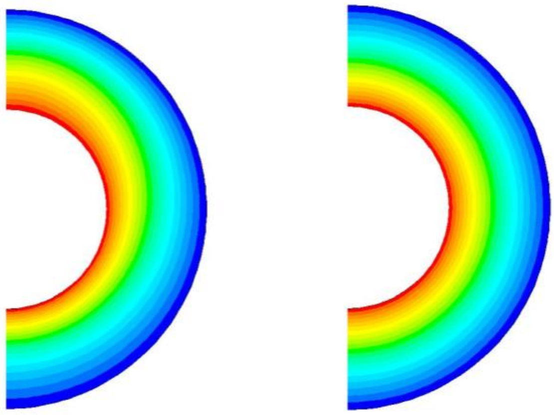

Fig. 2 (a)Gr=4893 temperature field (b) Gr=679 temperature field

4.2 Critical criterion

In addition, the calculation models of two working conditions of annulus enclosure are established, one is the high temperature of inner wall and the other is the low temperature of outer wall; The other is the low temperature of the inner wall and the high temperature of the outer wall. By comparing the results of numerical analysis and theoretical calculation, there is no significant difference in heat flux under the same conditions.

The analytical formula of heat flux for heat conduction of hollow cylinder is as follow:

$$q = \frac{2\pi k L \Delta T}{\ln\left(\frac{r_o}{r_i}\right)} \tag{8}$$

where L is the length of the annulus, it is equal to 1 in 2D problem .

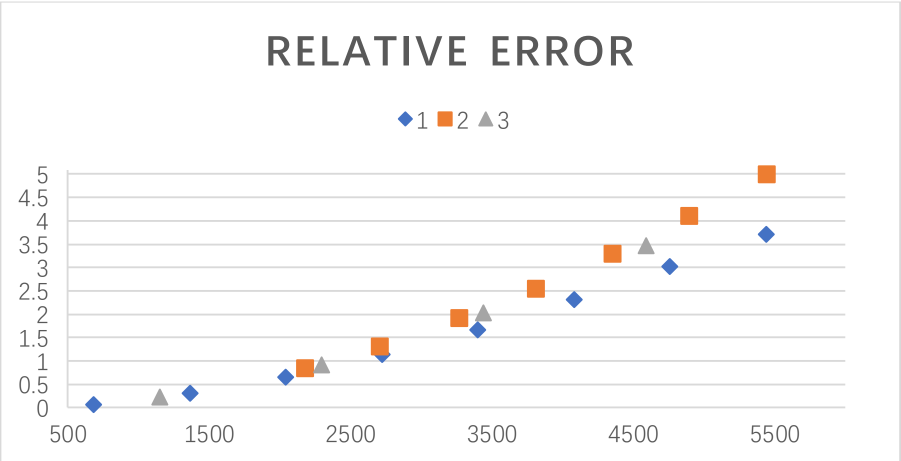

Fig. 3 Relative error chart (y axis is relative error %, x axis is Gr)

There are three geometric shapes in Fig.3, (1 2 3) represent δis equal to 1cm, 2cm and 1.5cm respectively. It can be seen from Fig.3 that with the increase of Gr number, the error from the analytical solution increases gradually, and interestingly, in the laminar flow region, the error changes approximately linearly with δ, There is a certain relationship, if δ increases and the error will be larger. However, there is no such phenomenon in the low Gr number region, which indicates that the low Gr number region is a complete heat conduction region. The larger the temperature is, the greater the natural convection effect is, which is consistent with the qualitative analysis. If the error of 1% is taken as the criterion, the critical value of pure heat conduction in annulus enclosure is Grc < 2500. And If Grc < 1000 is taken as the criterion, the relative error is only 0.2%.

5. CONCLUSION

This paper uses open-source software OpenFOAM. And using Incompressible fluid and Boussinesq hypothesis. In this paper, the natural convection in an annulus enclosure is studied. Several models are used to calculate different Gr, and the critical Gr value from heat conduction to natural convection is obtained. The main conclusions are as follows

1) If the relative error of 1% is taken as the criterion, the critical value of pure heat conduction in the annulus enclosure is about Gr=2500.

2) If Grc = 1000 is taken as the critical standard, the relative error is only 0.2%.

3) The calculation of Grc has nothing to do with the temperature of the inner and outer wall. It is applicable to both the high temperature of the outer wall and the high temperature of the inner wall, which is consistent with the theory solution. Because the calculation formula of pure heat conduction is only related to the temperature difference.

4) With the increase of Gr number, the isotherms gradually bend. Even if the critical Grc value is exceeded a lot, the heat conduction is still dominant near the inner and outer walls. However, with the increase of Gr number, the dominant region of heat conduction becomes smaller.

REFERENCES

[1] Holman, Heat Transfer(10th), McGraw-Hill Book Co. N.Y. ,2010, p350
[2] Zhang Ximin, Heat Transfer (5th), China Construction Industry Press,2007, p167-168
[3] Yang Shiming, Tao Wenquan, Heat Transfer (4th), higher education press,2006, p272
[4] Guo kuanliang, Chen Zhijian etc. Advanced Numerical Heat Transfer and Fluid Flow, Jiangsu University Press,2015
[5] Xu F, Cui H M. Natural convection in a differentially heated cavity. Advances in Mechanics, 2014, 44: 201403
[6] A. Bazylak, N. Djilali, and D. Sinton，Natural Convection in an Enclosure with Distributed Heat Sources，Numerical Heat Transfer, Part A, 49: 655–667, 2006
[7] JIANG Changjian , CHEN Gungming , LU Wancheng etc. A Numerical Simulation of Laminar Natural Convection in a Horizontal Concentric Cylindrical Annuli. Journal of Shanghai JiaoTong University, 1999, 33(3): 281-284
[8] Peng Lan,Liu Yu,Li, Yourong etc. Numerical Simulation on Natural Convection of Water Near the Maximum Density Horizontal Annulus. Journal of Chongqing University, 2008, 31(6):623-626
[9] Dong Qing,Sun,Li,He etc.. Experimental Study on Heat Transfer of Natural Convection between Horizontal Micro-wire and Water. Journal of Shandong University of Technology (Natural Science Edition), 2007, 21(5): 85-87
[10] Zou Jianfeng,Gao Ye. Numerical Investigation of Natural Convection in Square Cavity Containing Heated Circular Pipe. Journal of Thermal Science and Technology, 2007, 6(4): 326-330
[11] Zhou Junkai,Zhou Weikun,Chen Guobang.Discussion on Energy Storage Method of Combination of Internal and External. Cryogenics and Superconductivity , 2003, 31(3): 61-63
[12] LI Heng,Bai Bofeng Lu Jun etc.Experimental Study of Thermal Convection During the Water Solidication Process in Cylinder Cavity，Journal of Engineering Thermophysics，2006,27(6):977-980
[13] OpenFOAM User Guide [online]. Available:.http://www.openfoam.org
[14] H. G. Weller, G. Tabor, H. Jasak, and C. Fureby. A tensorial approach to computational continuum mechanics using object-oriented techniques, Computers in Physics 12, 620 (1998)
[15] T. Maric, Jens Höpken, K. Mooney .The OpenFOAM Technology Primer. Sourceflux
UG,2014