Vol. 40 No. 11 SCIENCE IN CHINA (Series A) November 1997

Ground simulation of flow and heat transfer under micro-gravity*

LIANG Xingang (梁新刚), GUO Zengyuan (过增元), LIU Yunlong (刘云龙)
and REN Jianxun (任建勋)

(Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China)

Received May 28, 1997

Abstract A new preservation technique is advanced, by which the flow and heat transfer in the manned spacecraft cabin can be simulated in the model on the ground with simultaneous preservation of temperature, material and Nusselt number. Numerical studies of flow and temperature fields in a cabin show that the gravity effect can be neglected if the scale of the model reduces to 1∶5, which corresponds to the ratio of Grashof number to the square of Renolds number smaller than the critical value. Below this value the natural convection is negligible.

Keywords: thermal scale modeling, preservation technique, microgravity, convective heat transfer.

Flow and heat and mass transfer under micro-gravity are usually concerned in fabrication of new materials and thermal management of manned spacecraft. Thermal scale modeling studies dealing with systems involving radiation-conduction-convection started in the 1960s[1]. Shannon[2] discussed such systems with emphasis on the spacecraft cabin atmosphere/cabin wall thermal interface and presented thermal similitude criteria and scaling techniques, including modified material preservation, temperature preservation, scaling compromises, Nusselt number preservation, etc. The modified material preservation technique uses the same gas as in the prototype and meets the scaling criteria by increased temperature. The temperature preservation technique keeps the same temperature as prototype and employs thermal conductivity scaled gas. The problems associated with the modified material preservation and temperature preservation scaling techniques limit their application. For useful application, the material (air in prototype) and temperature are expected to be all preserved, even some degree of similarity is sacrificed. The scaling compromise technique is such a kind of technique. It keeps the same gas in the model and prototype and approximately preserves the temperature. But a reduced pressure is required when the prototype is under zero-gravity. The Nusselt number preservation technique uses the thermal model to experimentally determine the Nusselt number for the system as a function of Reynolds and Grashof numbers. This functional relationship would then be used in conjunction with a thermal math model to predict the prototype performance. This technique keeps both the same temperature and gas in the model and avoids the problems inherent in other scaling techniques. It requires, however, the complicated experimental techniques and mathematical model while the other thermal scaling techniques need only the fabrication and testing of the scale model. The system becomes very complex when the radiation, conduction, convection are all involved except that sometimes only convective heat transfer is concerned. As a first step, the present study is confined to

---

* Project supported by the National Natural Science Foundation of China.

the problem of convective heat transfer in an enclosure with ventilation in terms of ground simulation method.

1 The temperature-material-Nusselt number preservation technique based on natural convection suppressed

For the manned spacecraft, the temperature in the cabin should be controlled within a specified range. As mentioned above, the preservations of both temperature and material (air) are demanded for available applications. The main problem for ground simulation is the gravity effect. When the manned spacecraft is in its orbit, the gravity acceleration is very small and there exists no or very weak natural convection in cabins. The forced convection due to ventilation is dominant in this case. But on the ground the natural convection is greatly enhanced because of the gravity and is comparable with, sometimes even exceeding, the forced convection caused by ventilation. Gravity could not be counteracted on ground except using the free fall methods. The free fall methods can supply zero/micro-gravity environment for no more than several minutes. Such a period of time is far from satisfying the thermal experiments that usually take hours. It is hence necessary to explore a new approach of ground simulation of micro-gravity environment. The influence of gravity induced natural convection depends on its relative importance to the forced convection. This can be seen from the non-dimensional equations of continuity, momentum and energy:

$$\nabla \cdot U = 0, \tag{1}$$

$$U \cdot \nabla U = \frac{1}{Re} \nabla^2 U - \frac{1}{Re^2} \nabla P - \frac{Gr}{Re^2} \Theta e_g, \tag{2}$$

$$U \cdot \nabla \Theta = \frac{1}{PrRe} \nabla^2 \Theta, \tag{3}$$

where e_g is unit vector of gravity acceleration, Gr is Grashof number, Pr is Prandtl number, Re is Reynolds number, U is non-dimensional velocity vector, Θ is non-dimensional temperature. If Re, Gr, Pr and non-dimensional boundary condition are maintained, the similarity of model to prototype is ensured. Pr is invariant when temperature and pressure of the air are preserved. Gr represents the intensity of natural convection and Re the forced convection. The last term in eq. (2) reflects the relative importance of the natural convection to forced convection. For similarity, Gr can be neglected if $Gr/Re^2 < A_{cr}$ in prototype. This implies that gravity influence can be neglected if $Gr/Re^2 < A_{cr}$. In fact, there exists a critical value for Gr/Re^2 below which the natural convection can be neglected. Under micro-gravity, the forced convection is dominant and the effect of natural convection is then negligible. On the ground the gravity is fixed, but Gr or Gr/Re^2 is changeable by different models. Because Gr is proportional to gL^3 and Re to uL, where L is the characteristic length of the enclosure. Gr decreases with L much faster than Re does. Thus, we can reduce L, that is, using small scale model to lower Grashof number and cut down the influence of gravity and to keep Re invariant by increasing velocity. Thus Gr/Re^2, smaller than the critical value, could be realized if proper scaled model is selected and consequently the influence of natural convection can be depressed; that is, the similarity of temperature and flow fields of model to prototype is obtained. Both temperature and material are preserved. Furthermore, the Nusselt number is also maintained because Nu is only the function of Re and Re is invariant under such conditions. This method may be referred to as "the temperature-material-Nusselt number preservation technique". In ref. [2], radiation-conduction-convection systems were discussed. The coupling of radiation and convection on the surface makes it impossible to preserve both temperature and material if the scale ratio is not 1∶1. The problems inherent in modified material preservation, temperature preservation and scaling compromise techniques come from the preservation of *Gr* and the coupling of radiation and convection. In the present case, where only convective heat transfer is considered instead of radiation-conduction-convection systems and Gr/Re^2 is smaller than the critical value instead of *Gr*, the preservations of temperature, material and Nusselt number are realized simultaneously.

2 Numerical verification

In this section the temperature-material-Nusselt number preservation technique will be further discussed with the aid of numerical method. It is useful to study the influence of gravity on flow and heat transfer[3—6]. Ref. [4] applied PHEONICS to assess the influence of gravity on flow and heat transfer for different inlet air velocity with the wall heated. The air inlets are located at the upper corner with the air flowing down while the outlets are situated at the bottom corner with the air going out horizontally. When the inlet velocity is 1m/s, the influence of gravity on flow and heat transfer was found to be negligible in prototype. Further studies are needed about the gravity effect on the flow and heat transfer in cabins for lower inlet velocity or different inlet air distribution.

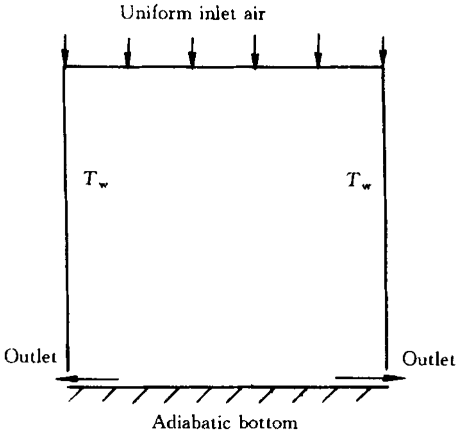


Fig. 1. Schematic structure of the enclosure configuration.

Numerical studies of flow and temperature fields have been carried out for a two-dimensional square area with full ceiling air supply and lateral air return at the bottom of two side walls (see fig. 1). Such a kind of ventilation is popular in clean rooms, accounting for its low cost and good flow pattern to dispose contamination[7]. The emphasis is placed on gravity effect and the discussion of the relative importance of natural convection and forced convection. The lateral walls are isothermally heated and the bottom wall is adiabatic. The air comes down from ceiling with uniform velocity and temperature. The outlets are one-twentieth of the length of the lateral walls. *Re*, *Gr* and computed *Nu* numbers for different scaled models are listed in table 1. A set of non-uniform grids of 42×52 is used to discrete momentum and energy equations of laminar flow by the control volume-based finite difference method. The grids are denser near the lateral walls where the temperature and velocity gradients are relatively high. SIMPLEC method is employed to solve the finite difference equations. The convergence criteria for all nodes are

$$|\phi_{i,j}^{n} - \phi_{i,j}^{n+1}| < 10^{-4}, \tag{4}$$

where ϕ denotes temperature or velocity at point (i, j), n and $n+1$ denote the times of iterations.

This code has been examined by the standard, two-dimensional square enclosure consisting of two adiabatic, horizontal walls and two vertical, isothermal walls that are differentially heated.

Table 1 The average Nu number of lateral wall for different scaled models

$g/\mathrm{m\cdot s^{-2}}$	0	9.8					
Scale ratio	1:1	1:1	1:2	1:3	1:4	1:5	1:6
$Gr\times10^8$	0	38.1	4.77	1.41	0.596	0.305	0.176
Gr/Re^2	0	207	25.9	7.67	3.23	1.66	0.958
Average Nu	74.2	128	100	84.7	75.2	71.6	72.6

The results of average Nusselt number are compared with ref. [8]. For Gr number up to 10^9, the departure of average Nusselt number is not more than 4%.

2.1 Average Nusselt number

The average Nusselt numbers of lateral walls for prototype under zero-gravity and for different scaled models under gravity are listed in table 1. With the reduction of scale model, the average Nusselt number gradually approaches that of prototype under zero-gravity, which indicates the depressing of the gravity influence. Fig. 2 illustrates the variation of Nu_m/Nu_0 with Gr/Re^2, where Nu_m represents the average Nusselt number at lateral wall and Nu_0 that of prototype under zero-gravity. It is seen from fig. 2 that when $Gr/Re^2<4.5$, the deviation of Nu_m from Nu_0 is smaller than 5%, which corresponds to the case with the scale ratio of 1:3.6.

2.2 Local Nusselt number

Though the average Nu of the small model agrees well with that of prototype under zero-gravity, the local Nusselt number distribution might differ very much. For similarity investigation, the examination of the local Nu number distribution and, furthermore, the flow pattern and isotherms are required. Fig. 3 demonstrates the local Nusselt number distribution at lateral wall for different scale models. At the scale ratio 1:4, the average Nusselt number is already very close to Nu_0, but the local Nusselt number distribution still differs much from that of prototype under zero-gravity. When the scale ratio comes to 1:5 that corresponds to $Gr/Re^2=1.66$, the distribu-

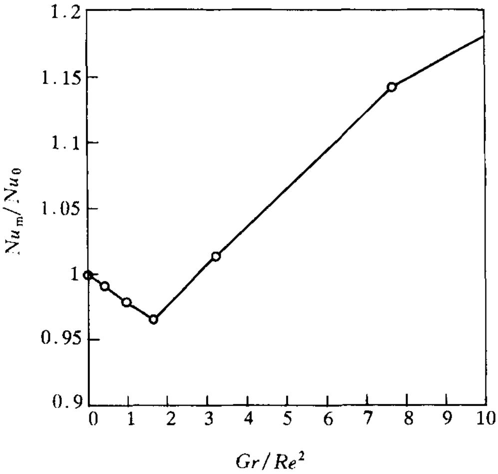


Fig. 2. The ratio of average Nu of lateral wall for different scaled model to that of prototype under zero-gravity vs. Gr/Re^2.

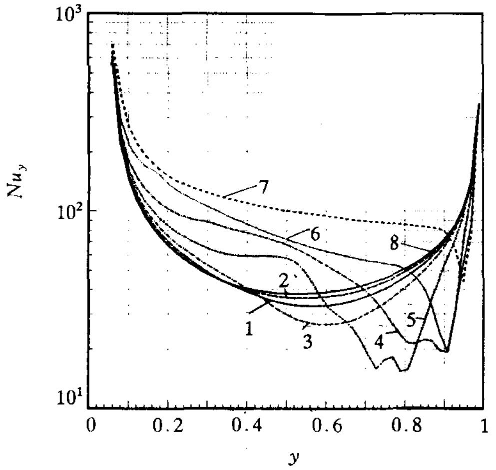
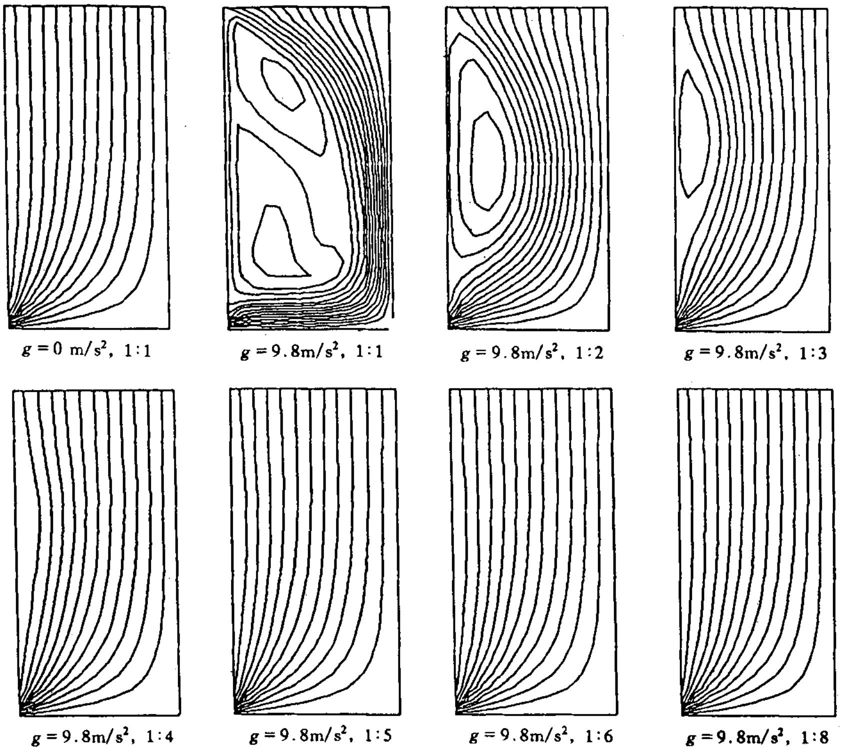


Fig. 3. The local Nusselt number distribution Nu_y vs. height y.

tions between them begin to agree with each other. For the scale ratio 1:6, the distributions of local *Nu* almost completely coincides with that of prototype under zero-gravity, i.e. when $Gr/Re^2 < 0.96$ the flow and heat transfer are identical with that of prototype under zero gravity.

2.3 Flow pattern and isotherms

The streamlines and isotherms are illustrated in figs. 4 and 5, which can be found consistent with local Nu distribution in fig. 3. Under zero-gravity, the air flows down from ceiling and goes out directly at bottom corners in the prototype. The gravity induced vortexes are produced near the lateral wall. With the reduction of model, vortexes gradually diminish and disappear at the scale ratio of 1:4. At the scale ratio of 1:5, both the flow patterns and isotherms are nearly identical with those of prototype under zero-gravity.



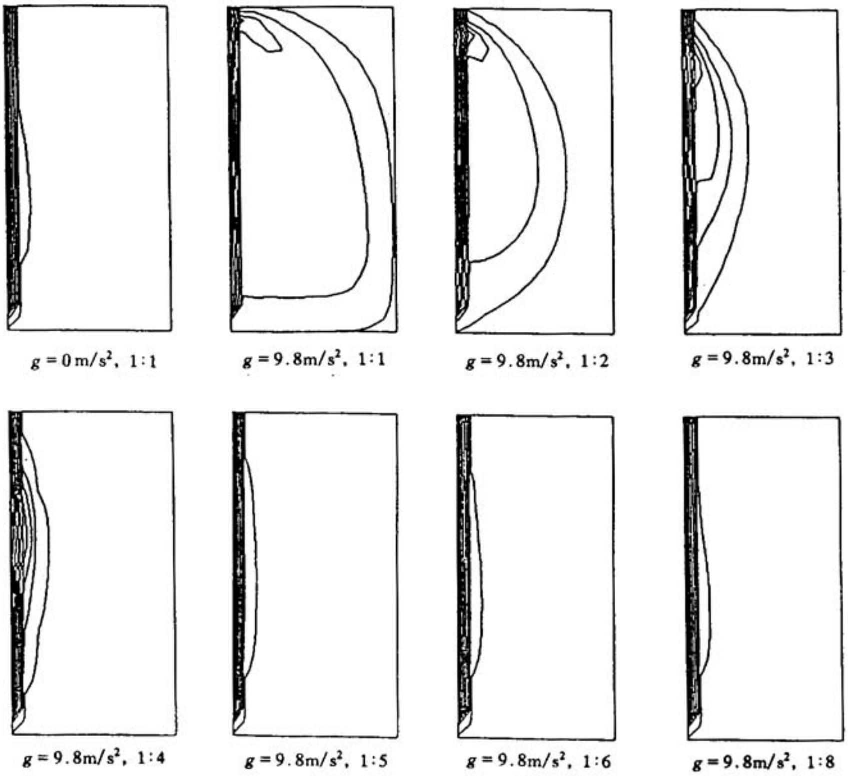
$g = 0$ m/s^2, 1:1 　 $g = 9.8$m/s^2, 1:1 　 $g = 9.8$m/s^2, 1:2 　 $g = 9.8$m/s^2, 1:3

$g = 9.8$m/s^2, 1:4 　 $g = 9.8$m/s^2, 1:5 　 $g = 9.8$m/s^2, 1:6 　 $g = 9.8$m/s^2, 1:8

Fig. 4. The streamlines for different scaled models.

3 Conclusion

In view of the fact that the forced convection is dominant in the manned spacecraft cabin, the flow and heat transfer under micro-gravity can be simulated by reducing the significance of buoyance in the mixed convection. Numerical results show that the gravity effect can be neglected if the scale of the model reduces to 1:4 or 1:5. Such a scale accords with the condition of the ratio of Grashof number to the square of Renolds number smaller than the critical value below which the natural convection is negligible. The present technique, referred to as the temperature-material-Nusselt number technique, can preserve the temperature, material, and the Nusselt number simultaneously.



$g = 0\,\mathrm{m/s^2}$, 1:1 $g = 9.8\,\mathrm{m/s^2}$, 1:1 $g = 9.8\,\mathrm{m/s^2}$, 1:2 $g = 9.8\,\mathrm{m/s^2}$, 1:3

$g = 9.8\,\mathrm{m/s^2}$, 1:4 $g = 9.8\,\mathrm{m/s^2}$, 1:5 $g = 9.8\,\mathrm{m/s^2}$, 1:6 $g = 9.8\,\mathrm{m/s^2}$, 1:8

Fig. 5. The isotherms for different scaled modes.

References

1 Klochzien, V. G., Shannon, R. L., Thermal scale modeling of spacecraft, *SAE Transactions*, 1969, 78:844.

2 Shannon, R. L., Thermal scale modeling of radiation-conduction-convection systems, *Journal of Spacecraft*, 1973, 10(8): 485.

3 Biringen, S., Danabasoglu, G., Computation of convective flow with gravity modulation in rectangular cavities, *Journal of Thermophysics*, 1990, 4(3):357.

4 Hofacker, W., Huchler, M., Analysis of the flow field in the HERMES cabin, *SAE Transactions*, 1990, 99:1.

5 Hufacher, W., Lucas, J., Zilly, F., Thermal analysis of spacecraft by combining different analysis tools, *SAE Transactions*, 1991, 100:1868.

6 Chang, H. S., Robert, S., Eugene, H., Numerical prediction and evaluation of space station intermodule ventilation and air distribution performance, *SAE Transactions*, 1994, 103:1387.

7 Wei, X. M., Li, B. T., Clean room with full ceiling air supply and lateral air return at the bottom of two side walls, in *Proceedings of Tsinghua-HVAC-'95*, September 25—27 (in Chinese), Beijing: Tsinghua University Press, 1995, 367.

8 Markatos, N. C., Pericleous, K. A., Laminar and tubulent natural convection in an enclosed cavity, *International Journal of Heat Mass Transfer*, 1984, 27(5):755.