A Numerical Method for Gravitational Condensate Flows with Structure

Satoru YAMAMOTO, Daisuke NIIYAMA**
and
*Byeong-Rog SHIN***

* *Dept. of Aeronautics and Space Engineering, Tohoku University, Sendai 980-8579, Japan*
** *Institute of Fluid Science, Tohoku University, Sendai 980-8577, Japan*

ABSTRACT

In most of the existing approaches for studying fluid-structure coupling problems, heat transfer in structure may be simulated separately from flow equations. Then, an equation of heat conduction is solved by a proper method such as a relaxation method. The purpose of this study is to develop a preconditioned implicit scheme for simulating condensate natural convections coupled with heat transfer in solid structure by solving a same system of fundamental equations. The preconditioned flux-splitting scheme developed by the authors[1] based on the preconditioning technique[2] is extended to the present fluid-structure coupling problems. This scheme has been applied to the Roe scheme[3] and the LU-SGS scheme[4]. The fundamental equations for transonic condensate viscous flows with homogeneous and heterogeneous nucleations[5] are transformed to the preconditioned equations by the preconditioning technique. By using the present method, thermal problems in solid structure can be also solved by the same equations for condensate flows. The reason why the thermal problems can be solved is simple, because no singularity problems occur in the preconditioned implicit scheme even when flow is completely static. If all velocities are zero in flow field, an equation of thermal diffusion in the thermal equation of incompressible Navier-Stokes equations is only solved by the time-marching method. Therefore, this scheme is quit valuable for the calculation of condensate flow and structure coupling problems.

The preconditioned flux-splitting scheme[1] is briefly explained in the following. The numerical flux $(F_i)_{\ell+1/2}$ defined at the interface between the control volume ℓ and $\ell+1$ in each coordinate $i\,(i=1,2,3)$ in the present fundamental equations can be written by a flux-splitting form as

$$(F_i)_{\ell+1/2} = \left(F_i^+\right)_{\ell+1/2} + \left(F_i^-\right)_{\ell+1/2} = \left(\hat{A}_i^+\right)_{\ell+1/2}\hat{Q}^L_{\ell+1/2} + \left(\hat{A}_i^-\right)_{\ell+1/2}\hat{Q}^R_{\ell+1/2}$$

where,

$$\left(\hat{A}_i^\pm\right)_{\ell+1/2}\hat{Q}^M = \left(\Gamma L_i^{-1}\Lambda_i L_i\right)_{\ell+1/2}\hat{Q}^M = \hat{\lambda}_{i1}^\pm \Gamma \hat{Q}^M + \frac{\hat{\lambda}_{ia}^\pm}{\hat{c}_i\sqrt{g_{ii}}}\hat{Q}_{ia} + \frac{\hat{\lambda}_{ib}^\pm}{\hat{c}_i^2}\hat{Q}_{ib}$$

and

$$\hat{\lambda}_{i1} = U_i,\quad \hat{\lambda}_{i3} = (1+\alpha)U_i/2 + \hat{c}_i\sqrt{g_{ii}},\quad \hat{\lambda}_{i4} = (1+\alpha)U_i/2 - \hat{c}_i\sqrt{g_{ii}}$$

$$\hat{c}_i = \sqrt{U_i^2(1-\alpha)^2/g_{ii} + 4U_r^2}\Big/2,\quad \alpha = U_r^2\left(\rho_p + \rho_T/\rho C_p\right)$$

$$\hat{\lambda}_{ij}^\pm = \left(\hat{\lambda}_{ij} \pm \left|\hat{\lambda}_{ij}\right|\right)/2,\quad \hat{\lambda}_{ia}^\pm = \left(\hat{\lambda}_{i3}^\pm - \hat{\lambda}_{i4}^\pm\right)/2,\quad \hat{\lambda}_{ib}^\pm = \left(\ell_i^-\hat{\lambda}_{i3}^\pm - \ell_i^+\hat{\lambda}_{i4}^\pm\right)/\left(\ell_i^- - \ell_i^+\right) - \hat{\lambda}_{i1}^\pm$$

$$\ell_i^\pm = \rho U_r^2/\left(U_i(1-\alpha)/2 \pm \hat{c}_i\sqrt{g_{ii}}\right),\quad \hat{U}_i = \left(\partial\xi_i/\partial x_j\right)\hat{q}_{j+1}^M \quad (j=1,2,3)$$

$$\hat{\boldsymbol{Q}}_{ia} = \hat{q}_1^M \boldsymbol{Q}_{ic} + \rho\hat{U}_i\boldsymbol{Q}_d,\quad \hat{\boldsymbol{Q}}_{ib} = \left(\rho\hat{U}_i\hat{c}_i^2/g_{ii}\right)\boldsymbol{Q}_{ic} + \left(\hat{q}_1^M\hat{c}_i^2/U_r^2\right)\boldsymbol{Q}_d$$

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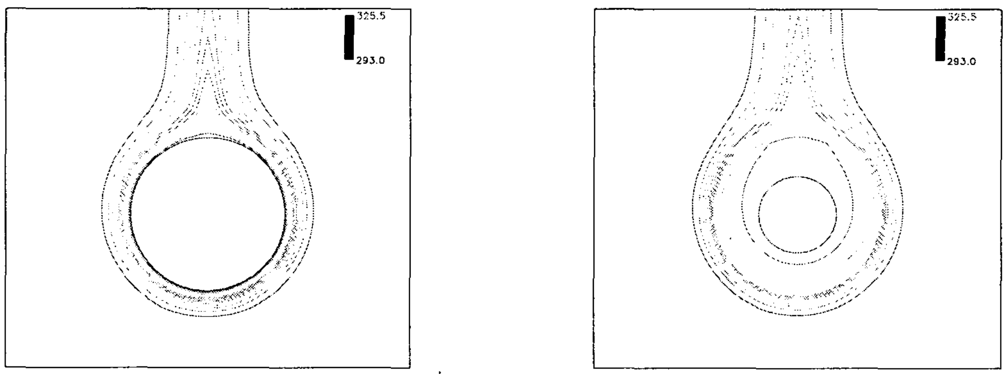
$g_{ii} = \nabla\xi_i \cdot \nabla\xi_i$. $\rho_p = \partial\rho/\partial p$. The upperscript M indicates the upperscript L or R. $\hat{q}_j$ is the j th element in $\hat{Q}$. $\hat{Q}$ is the vector of unknown primitive variables and $\hat{Q} = [\rho \quad u_1 \quad u_2 \quad u_3 \quad T \quad \rho_v/\rho \quad \beta \quad n]$. ρ, u_i, T , ρ_v, β and n are the density of mixed gas, the physical velocity components, the temperature, the density of vapor, the condensate mass fraction, and the number density of liquid particles, respectively. Q_{ic} and Q_d are subvectors.

In this abstract, only typical calculated results are shown as an image of the present method. Natural convections around a horizontal circular cylinder coupled with solid structure in the cylinder are calculated. As flow conditions, the uniform temperature far from the cylinder is 293[K]. Working gas is dry air. An O-type grid is used. It has 180x45 grid points. The gravitational force is added in the source term for the momentum and energy equations. The Rayleigh number is fixed at Ra=10^5. Figure 1(a) shows the calculated temperature contours when the surface temperature on the cylinder is fixed at 325.5[K]. A thermal plume is formed around the cylinder. On the other hand, Fig.1(b) shows the calculated temperature contours around the cylinder and in the solid structure. In this case, the inner wall of the solid region is fixed at 325.5[K] and heat conduction is calculated in the solid region by the present method. Temperature contours are observed in the solid structure as well as those around the cylinder.

Calculated results with condensation assuming atmospheric conditions have been already obtained, too. These results will be shown in the full paper.

References

1. S.Yamamoto and B.-R. Shin, Preconditioned Implicit Flux-splitting Scheme for Condensate Flows, Proc. 2nd Int. Conf. on Computational Fluid Dynamics-Sydney, (2002), Springer, in press.
2. J.M. Weiss and W.A. Smith, AIAA Journal, 33 (1995), pp.2050-2056.
3. P.L. Roe, J. Comp. Phys., 43 (1981), pp.357-372.
4. S.Yoon and A. Jameson, AIAA Journal, 26 (1988), pp.1025-1026.
5. S. Yamamoto, Onset of Condensation in Vortical Flow over Sharp-edged Delta Wing, Proc. 15th AIAA CFD Conference, AIAA Paper 2001-2651, (2001).



(a) without structure (b) with solid structure

Fig.1 Calculated temperature contours around cylinder and in solid structure