Cold Flow Simulation of SF_6 Puffer Circuit Breaker

Chae-Yoon Bae, Hyun-Kyo Jung, Sang-In Shin and Oh-Hyun Rho

Abstract - Numerical schemes for the simulation of the cold gas flow in the SF6 puffer type circuit breaker is presented. The governing equation is axisymmetric compressible Euler Equation and FVM is used to analyze the behavior of flow. The upwind scheme is used to avoid numerical instability and MUSCL is used to obtain high order accuracy. For the efficient calculation, AF-ADI scheme is used. The simulation result shows good agreement with the experimental data.

Keywords - Euler Equation, FVM, MUSCL, AF-AID, Upwind.

1. Introduction

All of supersonic, transonic and subsonic regions exist simultaneously in the gas flow of circuit breaker and numerical simulation may be unstable for this reason. Various methods like FDM (Finite Difference Method), FLIC (Fluid in Cell)[1], FEM (Finite Element Method) and FVM (Finite Volume Method)[2] are used to analyze the gas flow of circuit breaker. FDM is too sensitive to the shape of the gird system, and FLIC needs artificial viscosity for stable solution.

Flow simulation using FVM is introduced in this paper. Roe's FDS[3] (Flux Difference Splitting), one branch of upwind scheme, is used to get a stable solution and the scheme does not need artificial viscosity. To get high order accuracy MUSCL[4] (Monotone Upstream-centered Scheme for Conservation Law) is used. And AF-ADI (Approximate Factorization - Alternating Direction Implicit) is adopted for the efficient calculation.

2. Finite volume method

2.1 Governing Equation

The governing equation is a axisymmerric compressible Euler equation, which is alternative way to express conservation law.

The conservative form of Euler equation is described as

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+H=0 \tag{1}$$

where,

$$Q=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ \rho e\end{pmatrix},\ E=\begin{pmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (e+p)u\end{pmatrix},\ F=\begin{pmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ (e+p)v\end{pmatrix},\ H=\frac{1}{y}\begin{pmatrix}\rho v\\ \rho uv\\ \rho v^2\\ (\rho e+p)v\end{pmatrix} \tag{2}$$

ρ, u, v, e : density, axial direction velocity, radial direction velocity, energy

The first row of equation (2) means the mass conservation, second and third mean the momentum conservation, and the last row means the energy conservation.

All the variables shown in equation (2) are normalized to reduce numerical errors using bases of the density and the speed of sound of free space

It is convenient to map the physical domain into the computational domain of generalized curvlinear coordinate because most gas circuit breakers have complicated shapes. The physical domain values such as time t and x value, y value are transformed into the computational values of τ, ξ, η, respectively.

$$\begin{aligned}\tau&=t\\ \xi&=\xi(t,x,y)\\ \eta&=\eta(t,x,y)\end{aligned} \tag{3}$$

The derivatives of above variable can be computed using chain rule as follows.

$$\begin{aligned}&\xi_x=Jy_\eta,\quad \xi_y=-Jx_\eta,\quad \xi_t=-(x_\tau\xi_x+y_\tau\xi_y)\\ &\eta_x=-Jy_\xi,\quad \eta_y=Jx_\xi,\quad \eta_t=-(x_\tau\eta_x+y_\tau\eta_y)\end{aligned} \tag{4}$$

where $J^{-1}=x_\xi y_\eta-x_\eta y_\xi=volume$

then equation (1) and equation (2) can be rewritten as follows

$$\frac{\partial \hat{Q}}{\partial \tau}+\frac{\partial \hat{E}}{\partial \xi}+\frac{\partial \hat{F}}{\partial \eta}+\hat{H}=0 \tag{5}$$

where,

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$$\hat{Q}=\frac{1}{J}Q=\frac{1}{J}\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ \rho e\end{pmatrix}$$

$$\hat{E}=\frac{1}{J}(\xi_x E+\xi_y F)=\frac{1}{J}\begin{pmatrix}\rho U\\ \rho uU+\xi_x p\\ \rho vU+\xi_y p\\ (e+p)U-\xi_t p\end{pmatrix}$$

$$\hat{F}=\frac{1}{J}(\eta_x E+\eta_y F)=\frac{1}{J}\begin{pmatrix}\rho V\\ \rho uV+\eta_x p\\ \rho vV+\eta_y p\\ (e+p)V-\eta_t p\end{pmatrix}$$

$$\hat{H}=\frac{H}{J}, \tag{6}$$

where U, V are contravariant velocities which are perpendicular to $\xi, \eta = constant$ surface.

$$U=\xi_x u+\xi_y v+\xi_t$$
$$V=\eta_x u+\eta_y v+\eta_t \tag{7}$$

2.2 Upwind Scheme

In general, there are two numerical differencing schemes to calculate the flux that passes through the control volume. One is central differencing scheme and the other is upwind differencing scheme.

The central differencing scheme is simple and easy to implement but cannot produce robust solution[5] in hyperbolic problem. On the contrary, the upwind scheme can give stable solution without artificial viscosity for the differencing is performed in the considering the direction of flow.

The FVS (Flux Vector Splitting)[6,7] and the FDS (Flux Difference Splitting)[8] are both upwind schemes but FVS contains too much numerical viscosity so the accurate solution can be hardly obtained with this scheme.

Roe's FDS is used in this paper and it is known that the accurate solution can be obtained with the scheme even at the point of the abrupt gradient of flow.

When the Roe's FDS is applied, equation (1) can be rewiritten as,

$$\frac{1}{J}\frac{\Delta\hat{Q}}{\Delta t}+\frac{1}{\Delta x}\left(\hat{E}_{i+\frac{1}{2},j}-\hat{E}_{i-\frac{1}{2},j}\right)+\frac{1}{\Delta y}\left(\hat{F}_{i,j-\frac{1}{2}}-\hat{F}_{i,j-\frac{1}{2}}\right)=-\frac{1}{J}\hat{H} \tag{8}$$

If the conservative flux $\hat{E}_{i+1/2,j}$ is expressed in the first order conservative form of the upwind scheme,

$$\hat{E}_{i-\frac{1}{2},j}=\frac{1}{2}\{\hat{E}_{i,j}+\hat{E}_{i+1,j}-|\hat{A}|(Q_{i+1}-Q_i)\} \tag{9}$$

$$\hat{A}=\frac{\partial\hat{E}}{\partial Q}=\hat{A}(Q_i, Q_{i+1})$$

where, Q is obtained from Roe's average quantities which are defined as follows.

$$\hat{A}(Q_i, Q_{i+1})=\hat{A}(\overline{Q}), \qquad \overline{\rho}=\sqrt{\rho_i\,\rho_{i+1}}$$
$$\overline{u}=\frac{u_i\sqrt{\rho_i}+u_{i+1}\sqrt{\rho_{i+1}}}{\sqrt{\rho_i}+\sqrt{\rho_{i+1}}},$$
$$\overline{v}=\frac{v_i\sqrt{\rho_i}+v_{i+1}\sqrt{\rho_{i+1}}}{\sqrt{\rho_i}+\sqrt{\rho_{i+1}}}$$
$$\overline{h}=\frac{h_i\sqrt{\rho_i}+h_{i+1}\sqrt{\rho_{i+1}}}{\sqrt{\rho_i}+\sqrt{\rho_{i+1}}},$$
$$\overline{a}^2=(\gamma-1)\left[\overline{h}-\frac{1}{2}(\overline{u}^2+\overline{v}^2)\right]$$
$$h=e+\frac{p}{\rho} \tag{10}$$

With these values, the conservative quantities Q can be calculated, and eigenmartix of $\hat{A}$ can be obtained as equation (11).

$$\hat{A}=X\Lambda X^{-1} \tag{11}$$

If the difference of conservative quantities can be expressed with the combination of $\overline{e_k}$ which is eigenvectors of X, like

$$Q_{i+1}-Q_i=X\alpha=\sum_{k=1}^{4}\alpha_k\overline{e_k}, \tag{12}$$

then equation (8) can be expressed with the vector operation as follows.

$$|\hat{A}(\overline{Q})|(Q_{i+1}-Q_i)=(X|\Lambda|X^{-1})(X\overline{\alpha})=X|\Lambda|\overline{\alpha}$$
$$=\sum_{k=1}^{4}\alpha_k|\lambda_k|\overline{e_k} \tag{13}$$

the conservative flux of the Roe's FDS can be obtained using following formulation.

$$\hat{E}_{i+\frac{1}{2}}=\frac{1}{2}\left[\hat{E}(Q_i)+\hat{E}(Q_{i-1})-\sum_{k=1}^{4}\alpha_k|\lambda_k|\overline{e_k}\right] \tag{14}$$

$$\sum_{k=1}^{4}\alpha_k|\lambda_k|\overline{e_k} = |(\Delta Q)_1|+|(\Delta Q)_2|+|(\Delta Q)_3|+|(\Delta Q)_4|$$

where

$$|(\Delta Q)_1| = |\lambda_1|\left(\Delta\rho-\frac{\Delta p}{\overline{a}^2}\right)\begin{bmatrix}1\\ u\\ v\\ \frac{\overline{q}^2}{2}\end{bmatrix}$$

$$|(\Delta Q)_2| = |\lambda_2|\overline{\rho}\begin{bmatrix}0\\ \Delta u-\xi_x(\xi_x\Delta u+\xi_y\Delta v)\\ \Delta v-\xi_y(\xi_x\Delta u+\xi_y\Delta v)\\ \frac{\Delta\overline{q}^2}{2}-(\xi_x\overline{u}+\xi_y\overline{v})(\xi_x\Delta u+\xi_y\Delta v)\end{bmatrix}$$

$$|(\Delta Q)_{3,4}| = |\lambda_{3,4}|\left(\frac{\Delta p \pm \bar{\rho}\bar{a}(\tilde{\xi}_x \Delta u + \tilde{\xi}_y \Delta v)}{2\bar{a}^2}\right)\begin{vmatrix} 1 \\ \bar{u} \pm \tilde{\xi}_x \bar{a} \\ \bar{v} \pm \tilde{\xi}_y \bar{a} \\ \bar{h} \pm \bar{a}(\tilde{\xi}_x \bar{u} + \tilde{\xi}_y \bar{v}) \end{vmatrix} \quad (15)$$

where

$$q^2 = u^2 + v^2,$$
$$\tilde{\xi}_x = \frac{\xi_x}{|\nabla \xi|}, \quad \tilde{\xi}_y = \frac{\xi_y}{|\nabla \xi|}$$
$$\Delta\rho = \rho_{i+1} - \rho_i, \quad \cdots\cdots$$
$$\lambda_1 = \lambda_2 = [\tilde{\xi}_t + \tilde{\xi}_x \bar{u} + \tilde{\xi}_y \bar{v}]\frac{|\nabla \xi|}{J},$$
$$\lambda_{3,4} = [\tilde{\xi}_t + \tilde{\xi}_x \bar{u} + \tilde{\xi}_y \bar{v} \pm \bar{a}]\frac{|\nabla \xi|}{J} \quad (16)$$

The flux $\hat{F}$ can be obtained by replacing ξ with η.

2.3 MUSCL (Monotone Upstream-centered Scheme for Conservation Law)

The Roe's FDS can be applied to the problem that has wide range of velocity and can detect shock wave very sharply. But it has first order accuracy. The higher order accuracy calculation could be accomplished by the extrapolation of primitive variables.

$$Q^+_{i-\frac{1}{2}} = \left(1-\frac{\phi}{2}\chi\right)Q_i - \frac{\phi}{4}(1-\chi)Q_{i-1} + \frac{\phi}{4}(1+\chi)Q_{i+1}$$
$$Q^-_{i-\frac{1}{2}} = \left(1-\frac{\phi}{2}\chi\right)Q_{i+1} - \frac{\phi}{4}(1-\chi)Q_{i+2} + \frac{\phi}{4}(1+\chi)Q_i \quad (17)$$

The second order accuracy is obtained with the value $\chi = -1$ and third order accuracy is obtained with the value $\chi = 1/3$. This high resolution scheme expressed in equation (17) is called MUSCL. But this extrapolation can violate the entropy condition and can produce oscillating or non physical solution. To avoid such troubles, TVD(Total Variation Diminishing) scheme is requested with the limiter which is nonlinear compensation factor. There are many kind of limiters and the Koren limiter is used in this paper. The formulation of Koren limiter with MUSCL is expressed in equation (18).

$$Q_{i+\frac{1}{2}} = Q_i - \frac{s}{4}[(1-\chi)\nabla + (1+\chi)\triangle]Q_i$$
$$Q^-_{i+\frac{1}{2}} = Q_{i-1} - \frac{s}{4}[(1+\chi)\nabla + (1-\chi)\triangle]Q_{i-1} \quad (18)$$

where,

$$s = \frac{3\triangle\nabla + \varepsilon}{2(\triangle - \nabla)^2 + 3\triangle\nabla + \varepsilon}, \quad \varepsilon \le 1 \times 10^{-6}$$

2.4 AF-ADI (Alternating Direction Implicit)

There are two kind of methods for the time integration. One is explicit method and the other is implicit method. The explicit method is easy to implement and costs small calculation time. But the explicit method is severely limited by the time interval. On the other hand, the implicit method is less limited by time interval than the explicit scheme, but costs more calculation time.

The implicit method was used with the backward difference of the Euler equation and the cost of calculation time is save with the ADI scheme.

The governing equation is rewritten in equation (19).

$$\frac{1}{J}\frac{\Delta \hat{Q}}{\Delta t} + \left[\frac{\partial \hat{E}}{\partial \xi}\right]^{n+1} + \left[\frac{\partial \hat{F}}{\partial \eta}\right]^{n+1} + \alpha(\hat{H})^{n+1} = 0 \quad (19)$$

The equation (20) can be linearized with the Taylor expansion

$$\hat{E}^{n+1} = \hat{E}^n + \frac{\partial \hat{E}}{\partial \hat{Q}}(\hat{Q}^{n+1} - \hat{Q}^n) + O(\Delta t^2) \approx \hat{E}^n + \hat{A}\Delta\hat{Q}$$
$$\hat{F}^{n+1} = \hat{F}^n + \frac{\partial \hat{F}}{\partial \hat{Q}}(\hat{Q}^{n+1} - \hat{Q}^n) + O(\Delta t^2) \approx \hat{F}^n + \hat{B}\Delta\hat{Q} \quad (20)$$
$$\hat{H}^{n+1} = \hat{H}^n + \frac{\partial \hat{H}}{\partial \hat{Q}}(\hat{Q}^{n+1} - \hat{Q}^n) + O(\Delta t^2) \approx \hat{H}^n + \hat{C}\Delta\hat{Q}$$

where $\hat{A}$, $\hat{B}$ is flux Jacobian

$$\hat{A} = \frac{\partial \hat{E}}{\partial \hat{Q}}, \quad \hat{B} = \frac{\partial \hat{F}}{\partial \hat{Q}}, \quad \hat{C} = \frac{\partial \hat{H}}{\partial \hat{Q}} \quad (21)$$

combining equation (20) with equation (19),

$$\frac{1}{J}\frac{\Delta \hat{Q}}{\Delta t} + \frac{\partial}{\partial \xi}[\hat{E}^n + \hat{A}\Delta\hat{Q}] + \frac{\partial}{\partial \eta}[\hat{F}^n + \hat{B}\Delta\hat{Q}] + \alpha[\hat{H}^n + C^n\Delta\hat{Q}] = 0 \quad (22)$$

$$\left[\frac{I}{J\Delta t} + \frac{\partial \hat{A}}{\partial \xi} + \frac{\partial \hat{B}}{\partial \eta} + \alpha\hat{C}\right]\Delta\hat{Q} = -\left[\frac{\partial \hat{E}^n}{\partial \xi} + \frac{\partial \hat{F}^n}{\partial \eta} + \hat{H}^n\right] \quad (23)$$

$$\left[\frac{I}{J\Delta t} + \delta_\xi^- \hat{A}^+ + \delta_\xi^+ \hat{A}^- + \delta_\eta^- \hat{B}^+ + \delta_\eta^+ \hat{B}^- + \alpha\hat{C}\right]\Delta\hat{Q} = -R^n_{i,j} \quad (24)$$

where $R^n_{i,j}$ is

$$R^n_{i,j} = \left[\frac{\partial \hat{E}}{\partial \xi} + \frac{\partial \hat{F}}{\partial \eta} + \hat{H}\right]^n \quad (25)$$

The left hand side of equation (24) is pentadiagonal matrix therefore its inverse matirx cannot be obtained quickly. In this paper the approximate factorization scheme is adopted and the pantadiagonal matirx is transformed into two block tridiagonal matrixes.

Equation (25) can be approximated as follows.

$$\left[\frac{I}{J\Delta t}+\delta_\xi^- \hat{A}^+ +\delta_\xi^+ \hat{A}^-\right]\frac{J\Delta t}{I}\left[\frac{I}{J\Delta t}+\delta_\eta^- \hat{B}^+ +\delta_\eta^+ \hat{B}^- +\alpha\hat{C}\right]\Delta\hat{Q}=-R^n_{i,j} \tag{26}$$

and equation (26) can be splitted into two steps.

$$\left[\frac{I}{J\Delta t}+\delta_\xi^- \hat{A}^+ +\delta_\xi^+ \hat{A}^-\right]\Delta\hat{Q}^*=-R^n_{i,j}$$
$$\left[\frac{I}{J\Delta t}+\delta_\eta^- \hat{B}^+ +\delta_\eta^+ \hat{B}^- +\alpha\hat{C}\right]\Delta\hat{Q}=\frac{I}{J\Delta t}\Delta\hat{Q}^* \tag{27}$$

then, the left hand side of equation (27) is expanded as follows

$$\left[\frac{I}{J\Delta t}+\hat{A}^+_{i,j}-\hat{A}^+_{i-1,j}+\hat{A}^-_{i+1,j}-\hat{A}^-_{i,j}\right]\Delta\hat{Q}^*=-R^n_{i,j}$$
$$\left[\frac{I}{J\Delta t}+\hat{B}^+_{i,j}-\hat{B}^+_{i,j-1}+\hat{B}^-_{i,j+1}-\hat{B}^-_{i,j}+\alpha\hat{C}\right]\Delta\hat{Q}=\frac{I}{J\Delta t}\Delta\hat{Q}^* \tag{28}$$

As a result,

$$-\hat{A}^+_{i-1,j}\Delta\hat{Q}^*_{i-1,j}+\left[\frac{I}{J\Delta t}+\hat{A}^+_{i,j}-\hat{A}^-_{i,j}\right]\Delta\hat{Q}^*_{i,j}+\hat{A}^-_{i+1,j}\Delta\hat{Q}^*_{i+1,j}=-R^n_{i,j}$$
$$-\hat{B}^+_{i,j-1}\Delta\hat{Q}_{i,j-1}+\left[\frac{I}{J\Delta t}+\hat{B}^+_{i,j}-\hat{B}^-_{i,j}+\alpha\hat{C}\right]\Delta\hat{Q}_{i,j}+\hat{B}^-_{i,j+1}\Delta\hat{Q}_{i,j-1}=\frac{I}{J\Delta t}\Delta\hat{Q}^* \tag{29}$$

The right hand side of equation (29) is expressed as in equation (30) with the MUSCL.

$$R^n_{i,j}=\left[\hat{E}_{i+\frac{1}{2},j}-\hat{E}_{i-\frac{1}{2},j}+\hat{F}_{i,j+\frac{1}{2}}-\hat{F}_{i,j-\frac{1}{2}}+\alpha\hat{H}\right]^n \tag{30}$$

2.5 Initial and boundary conditions

At initial time the fluid does not move and the values of normalized variables is were set as follows.

$$\rho_\infty=1,\quad u_\infty=0,\quad v_\infty=0,\quad p_\infty=\frac{1}{\gamma},$$
$$e_\infty=\frac{1}{\gamma(\gamma-1)}+\frac{1}{2}M^2_\infty \tag{31}$$

Velocity at the wall boundary can be obtained from the relation between the contravariant velocity and the Cartesian coordinate.

$$U=\xi_t+\xi_x u+\xi_y v$$
$$V=\eta_t+\eta_x u+\eta_y v \tag{32}$$

$$\therefore\begin{pmatrix}u\\v\end{pmatrix}=\begin{bmatrix}\xi_x & \xi_y\\ \eta_x & \eta_y\end{bmatrix}^{-1}\begin{pmatrix}U-\xi_t\\V-\eta_t\end{pmatrix}=\frac{1}{J}\begin{bmatrix}\eta_y & -\xi_y\\ -\eta_x & \xi_x\end{bmatrix}\begin{pmatrix}U-\xi_t\\V-\eta_t\end{pmatrix} \tag{33}$$

In case of nonviscous flow, $U_1=U_2$ and $V_1=-V_2$. Equation (33) can be expressed as follows

$$u_1=-\frac{2\xi_y(\eta_x x_\tau+\eta_y y_\tau)}{J}+u_2-\frac{2\eta_x}{\eta_x^2+\eta_y^2}V_2$$
$$v_1=-\frac{2\xi_x(\eta_x x_\tau+\eta_y y_\tau)}{J}+v_2-\frac{2\eta_x}{\eta_x^2+\eta_y^2}V_2 \tag{34}$$

The position of farfield boundary is limited for economical calculation and the solution of wave equation can be used instead of infinite farfield. In this paper non-reflecting condition which is the solution of the one dimensional wave equation is used for the farfiel boundary.

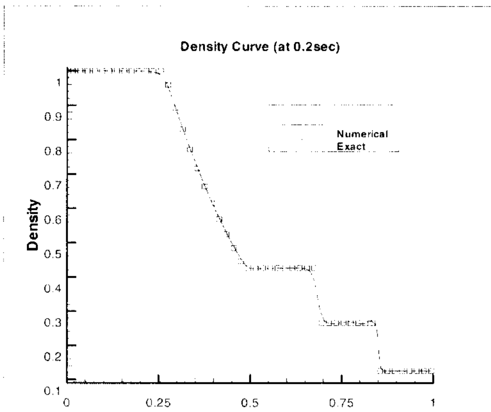
$$\frac{\partial p}{\partial t}-\rho c\frac{\partial u}{\partial t}+\alpha(p-p_\infty)=0 \tag{35}$$

where α was empirically determined.

3. Verification of unsteady solution

The shock tube problem is solved for the verification of unsteady solution. With the initial condition shown in Fig. 1 the membrane was removed at time = 0. This problem has analytic solution and the validness of the schemes and the code were checked.

As shown in Fig. 1 the numerical solution has good agreement with the analytic solution.



density 1 pressure 1	density 0.125 pressure 0.1

Fig. 1 Initial condition of shock tube and calculation result

4. Simulation and Result

The puffer type circuit breaker is analyzed. The total number of cells was about 32,000. The cells of grid system were added or removed as the piston and the electrode move.

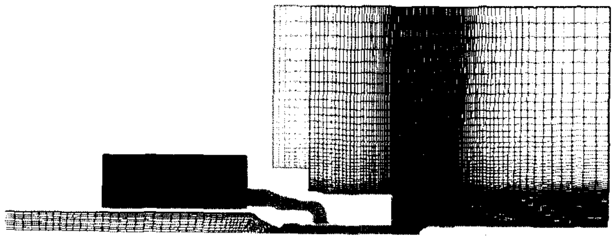
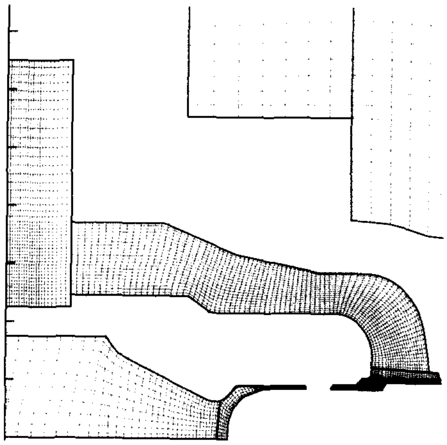
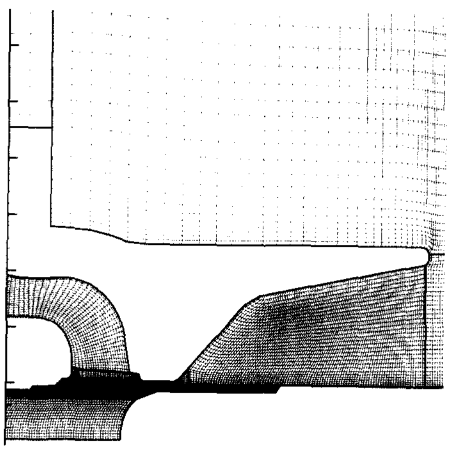


Fig. 2 Analyzed model and its grid system

The number of blocks is 16 and each block has different grid spacing.



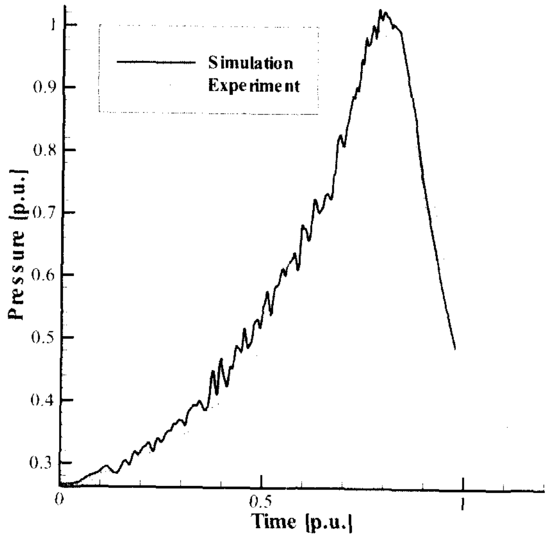
(a) gird system around nozzle throat



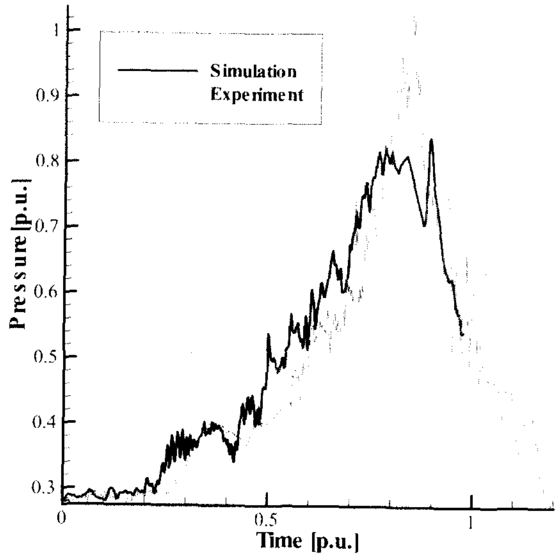
(b) grid system around nozzle end

Fig. 3 Close-up view of grid system around nozzle

The gird system around nozzle is very important because the flow around nozzle varies rapidly and the shocks also occur at these points. The shocks dominate the electrical and fluid dynamical properties.

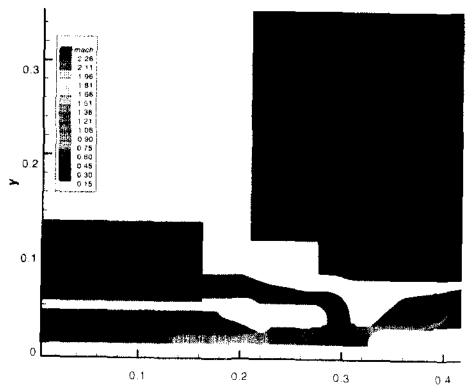


(a) pressure change on the piston

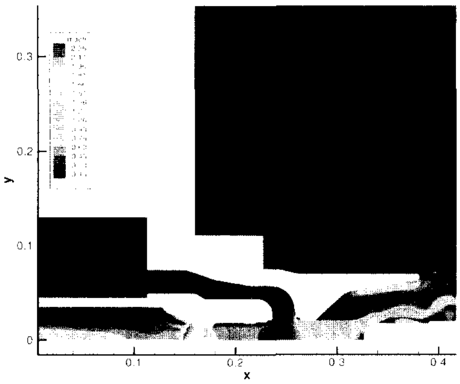


(b) pressure change on the fixed electrode

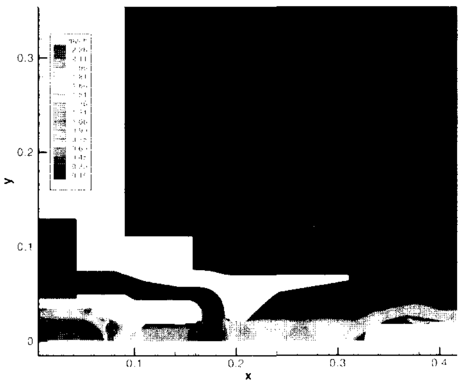
Fig. 4 Comparison of simulation result with Experiment



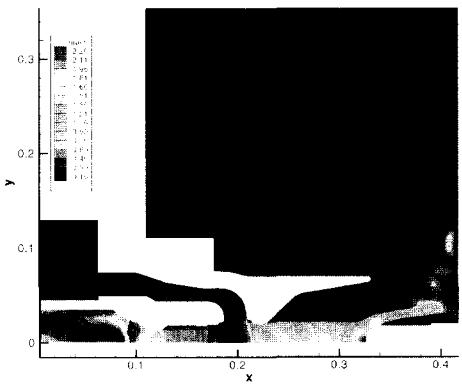
(a) Time: 0.47



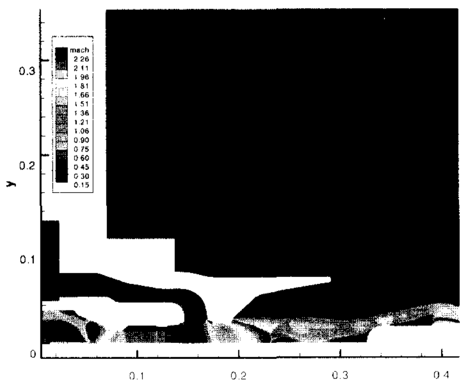
(b) Time: 0.61



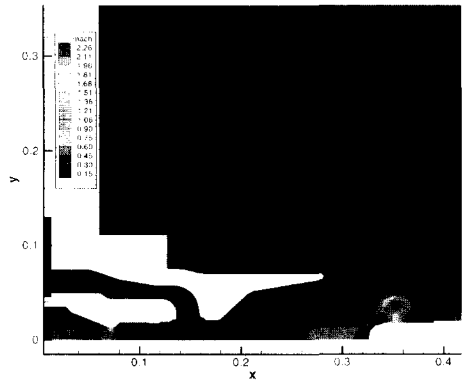
(c) Time: 0.75



(d) Time: 0.83

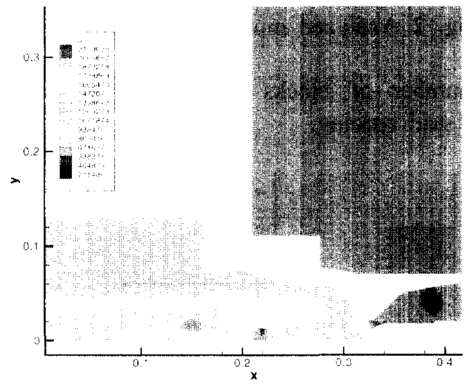


(e) Time: 1.0

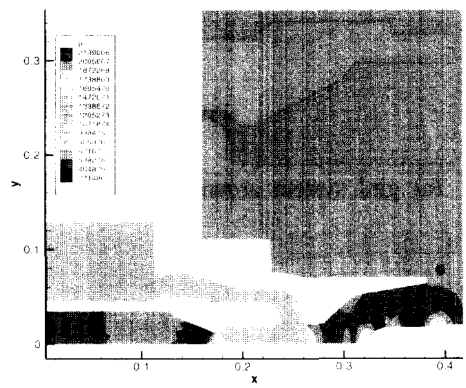


(f) Time: 1.1

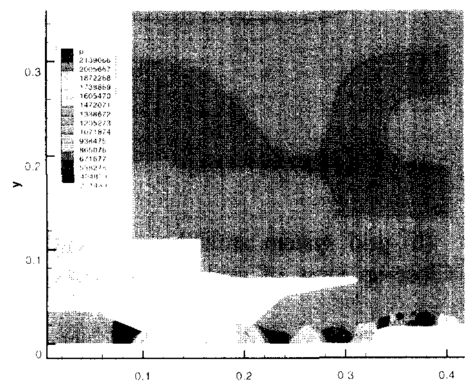
Fig. 5 Change of the mach number distribution



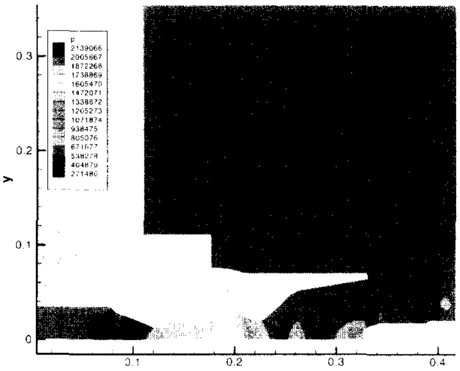
(a) Time: 0.47



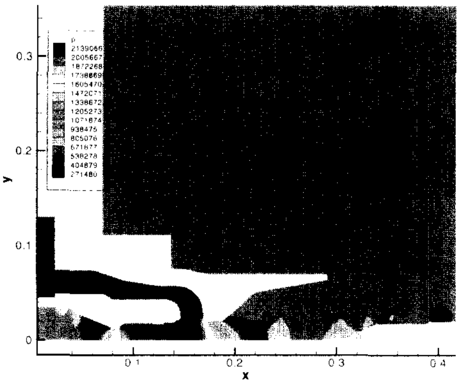
(b) Time: 0.61



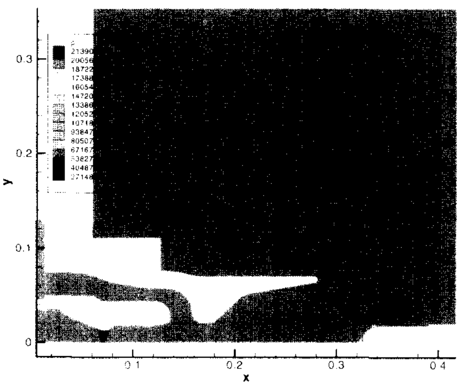
(c) Time: 0.75



(d) Time: 0.83



(e) Time: 1.0



(f) Time: 1.1

Fig. 6 Change of the pressure distribution

As shown in Fig. 4, the simulation result has good agreement with experimental data. The pressure on the electrode changes very rapidly because of the shock wave that occurs in front of the fixed electrode and this may make it hard to get the accurate simulation result.

Fig. 5 shows the change of mach number distribution according to time and the occurrence of shock, at mach number is 1, is clearly showed. This shock wave dominates the values of pressure and density and the sharp simulation of shock wave both in space and time guarantees the accuracy of simulation. Fig. 6 shows the change of pressure distribution according to time and, in nature, the close relation between mach distribution and pressure can be verified.

5. Conclusion

Cold flow simulation in puffer circuit breaker is presented. FVM with the schemes of Roe's FDS upwind scheme, MUSCL, and AF-ADI worked very well in obtaining high resolution, robust numerical solution in circuit breaker flow simulation without much calculation time.

The simulation result shows good agreement with experimental data and this exact result would be a contribution to exact prediction of dielectric recovery strength or small current breaking characteristic.

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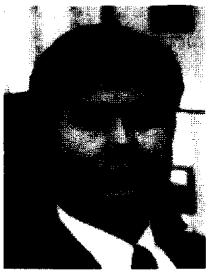

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