Numerical Simulation of Gasification Process on Rib-tube of Open Rack Vaporizer

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Abstract—The gasification progress which was coupled between heat transfer and fluid-flow on rib-tube of Open Rack Vaporizer (ORV) was studied in this paper. Based on theoretical analysis and experiment, the $k - \varepsilon$ model and wall-function were chose to simulate the flow field of rib-tube, and the multiphase flow was described by the mixture model, in which the dispersed phase was defined by different velocity. In addition, self-defining functions were used and governing equations were set up to solve the dispersed phase, and the results were compared with the experiment. The process of fluid-flow and heat exchange on rib-tube was simulated, and the contours of temperature, pressure, velocity, gas fraction were obtained, which showed that, the parameters of above changed when the temperature rises and the LNG evaporate along the rib-tube, and a mixed process existed in the middle of the heat tube.

Index Terms—Open Rack Vaporizer (ORV); Rib-tube; wall-function; Numerical simulation; Gasification

I. INTRODUCTION

Open Rack Vaporizer (ORV) is a kind of heat exchanger widely used in liquefied natural gas (LNG) terminal, which is mainly comprised by rib-tubes. In the researches of rib-tube, fluid parameters, flow characteristics and the heat transfer were concerned[1-9]. Wung et al[2] simulated the two-dimensional model of many kinds of rib-tube in order to find the flowing rules; Guannan Xi et al[3] compared the differences between two-dimensional simulation and three-dimensional simulation on rib-tubes and point out the difficulties of three-dimensional simulation. Torikoshi and Xi G N[4] researched the three-dimensional fluid-flow and heat transfer on one and two rows of rib-tubes, and concluded that three-dimensional numerical simulation was conducive to the mechanism analysis of fluid-flow and heat transfer , which could predict the actual heat transfer performance of the heat exchanger, however, improving the computational difficulties largely. Aytunc

Erek et al[5] studied the heat transfer and flow on straight-tube, and gave the best geometric parameters to describe the influence of the heat transfer coefficient and pressure drop.

According to author's investigation, there were few studies related on physical field, two-phase flow analysis and test comparison in the researches of flow and heat transfer on rib-tube of ORV. On the basis of theoretical study, numerical simulation and comparison with experimental results, this paper gave the gasification process and distributive rules of temperature, velocity, pressure and gas holdup when the temperature rising along the rib-tube . The working principle sketch for rib-tube of ROV was shown in Fig.1.

II. THE MATHEATICAL MODEL AND CONTROL EQUATION
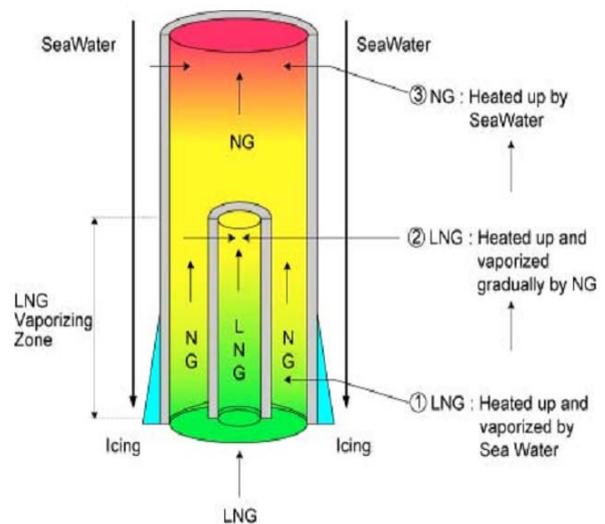
A. Turbulent Flow Model

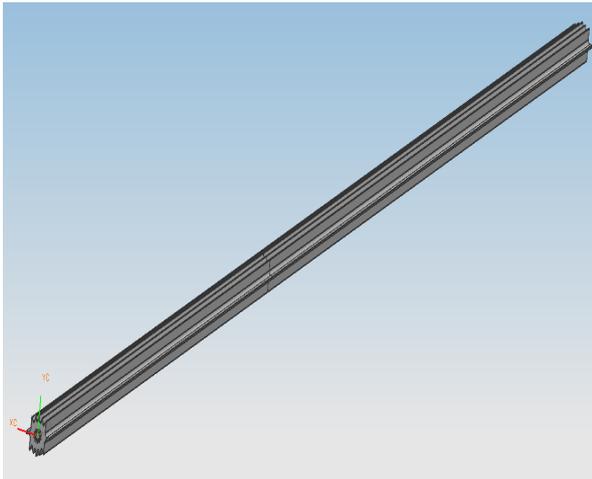Fig.1: Working principle sketch for rib-tube of ROV

Fig.2: Flow field model of rib-tube

$k - \varepsilon$ model is the semi-empirical formula summed up from experimental phenomenon, which assumes that flow field is completely turbulent, and ignores the adhesion between the molecules, mainly applied to the turbulent region leaving a certain distance from the wall surface, and it's a high Reynolds number model. Wall Function method is an effective way to treat the flow near the wall.

When standard $k - \varepsilon$ model was used to solve the problem of flow and heat exchange, the governing equations, including the continuity equation, momentum equation, energy equation, the k equation, and the ε equation, could be expressed as the following general form:

$$\frac{\partial}{\partial t}(\rho \phi) + \frac{\partial}{\partial x}(\rho u \phi) + \frac{\partial}{\partial y}(\rho v \phi) + \frac{\partial}{\partial z}(\rho w \phi)$$
$$= \frac{\partial}{\partial x}\left(\Gamma \frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma \frac{\partial \phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(\Gamma \frac{\partial \phi}{\partial z}\right) + S \qquad (1)$$

Where, ϕ was a universal variable which could be representative of variables such as $u, v, \ p, T, k, \varepsilon$; Γ was the generalized diffusion coefficient; S was the generalized source term.

B. Multiphase Flow Model

In the rib-tube of ORV, LNG become to NG, the mixture model was chosen to describe the gas-liquid two-phase flow progress, and the mixture model calculation equation were as follows:

Continuity equation:

$$\frac{\partial}{\partial t}(\rho m) + \nabla \cdot (\rho_m \vec{v}_m) = \dot{m} \qquad (2)$$

Where, $\vec{v}_m$ was the quality of the average speed; ρ_m was mixed density:

$$\vec{v}_m = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_k}{\rho_m} \qquad (3)$$

$$\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k \qquad (4)$$

α_k was volume fraction of k phase; ρ_k was density of k phase;

$\dot{m}$ described the mass transfer of user-defined quality source.

Momentum equation

$$\frac{\partial}{\partial t}\left(\rho_m \vec{v}_m\right) + \nabla \bullet \left(\rho_m \vec{v}_m\right) = -\nabla p + \nabla \bullet \left[\mu_m \left(\nabla \vec{v}_m + \nabla \vec{v}_m^{T}\right)\right]$$
$$+ \rho_m \vec{g} + \vec{F} + \nabla \bullet \left(\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k}\right) \qquad (5)$$

n was the number of phase; $\vec{F}$ was volume force and μ_m was mixing viscous; $\vec{v}_{dr,k}$ was the drift velocity of the second phase k:

$$\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k \qquad (6)$$

$$\vec{v}_{dr,k} = \vec{v}_k - \vec{v}_m \qquad (7)$$

Energy equation:

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}\left(\alpha_k \rho_k E_k\right) + \nabla g \sum_{k=1}^{n}\left(\alpha_k \vec{v}_m \left(\rho_k E_k + p\right)\right) \qquad (8)$$
$$= \nabla g \left(k_{eff} \nabla T\right) + S_E$$

Where,

$$E_k = h_k - \frac{p}{\rho_k} + \frac{v_k^2}{2} \qquad (9)$$

k_{eff} was effective thermal conductivity, the first term to the right of equation above represented the energy conduction caused by the transfer; S_E contained all of the volume of heat source.

III. LATION METHOD OF GASIFICATION PROCESS IN TUBE

User-defined functions (UDF) written in C language by the users were used to calculate the gasification process of LNG, which were dynamically connected to the Fluent Solver up to improve the performance of the solver, and were defined by DEFINE macro. Adding mass source term to the mass equation is a method to approximately simulate the phase change processes that happening in the rib-tube [6].

IV. ITE ELEMENT MODEL

A. Flow Field Model

According to the cross-sectional structure of rib-tube, UG software was used to build the model of flow field which was shown in Fig.2, Z direction was along the tube.

B. Finite Element Model

Considering the structure outside wall and meshing time, unstructured hexahedral grid was chosen to mesh the rib-tube, and the grid number was 46.1 million. Due to the volume mesh was generated by Cooper method, the meshing quality could be controlled. The flow field grid was shown in Fig.3.
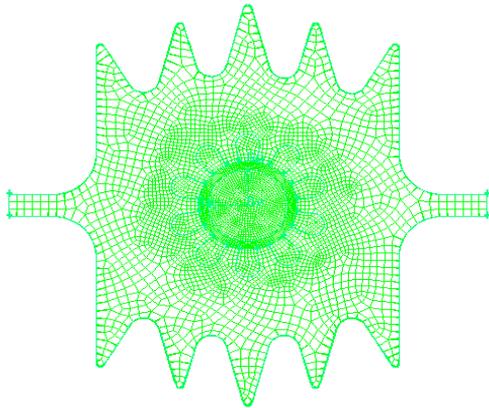

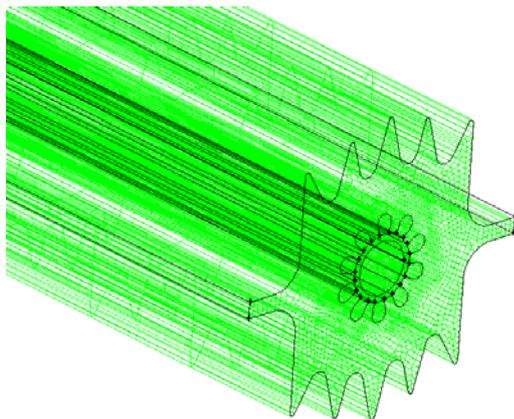
Fig.3(a): Local grid map for the flow field of rib-tube

Fig.3(b): Local grid map for the flow field of rib-tube

C. Boundary Conditions and Flow Field Calculation Set

Based on the mixture model and the $k-\varepsilon$ model, and considering the impact of acceleration of gravity, Grid model generated by Gambit was imported into solver of Fluent6.3.Before calculation, material properties, the main phase and other phases of multiphase, boundary conditions, initial state, and operating pressure (10MPa) were set up, and relevant physical parameters were also given which were listed in Table I.

TABLE I.

RELEVANT PHYSICAL PARAMETERS

	Density (kg/m^3)	Viscosity $(m \cdot Pa \cdot s)$	Heat capacity at constant pressure $(J/(kg \cdot K))$	Thermal conductivity $(W/(m \cdot K))$	Molecular
LNG	453.5	0.1335	3158	0.1962	17.08
NG	104.9	0.0146	3455	0.04448	17.08
Al6063	2680	—	900	201	—

According to the data provided above, the boundary conditions for LNG inlet was velocity inlet and NG outlet was pressure outlet, outside wall was temperature, imports and exports ends were both adiabatic surfaces, and others were coupled walls. Mass term was added to LNG and NG respectively in the tube, which were defined by UDF program. The boundary diagram was shown in Fig.4.
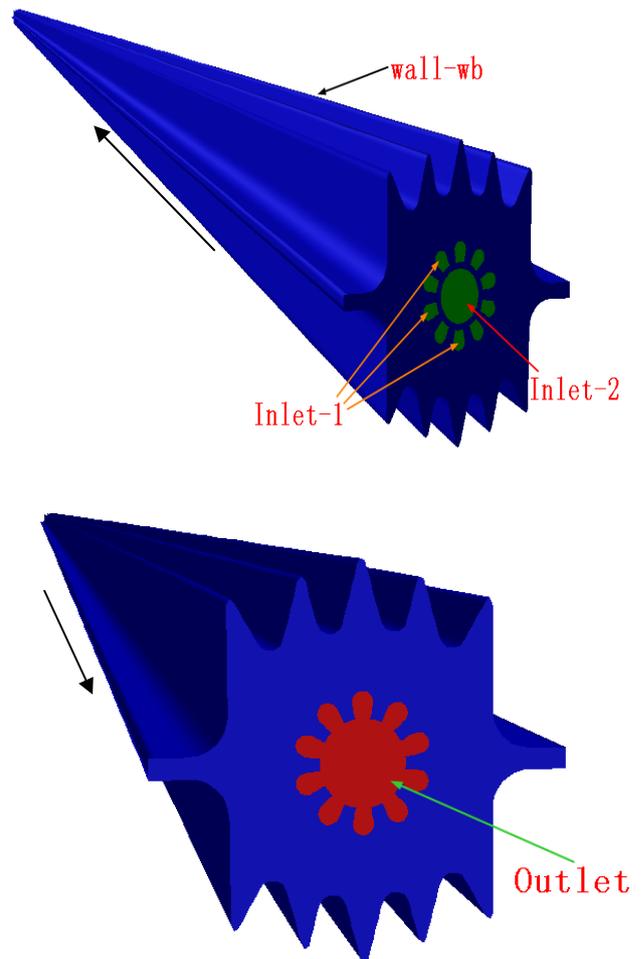

Fig.4: The boundary conditions for rib-tube

Considering the complex process composed of phase change, flow and heat transfer happening in rib-rube, the discrete control equation was first-order upwind scheme

and standard pressure difference format, and SIMPLE algorithm was applied to solve the coupled pressure-velocity. First, solve the adiabatic flow which was not coupled to the energy equation iteration; second, join the energy equation of flow field after getting the converged solution; at last, gain a complete solution for this flowing process. The convergence criteria for residuals were less than 10-3, the energy equation residuals were less than 10-6, and the exit velocity and temperature values were basically stable.

V. NUMERICAL RESULTS DISCUSSION

A lot of theoretical research for ORV was done by our team, and we designed and manufactured an experimental prototype, on which preliminary experiments were carried out.

According to mathematical model and the method for solving, we simulated the process of flow and heat transfer and compared the theoretical calculative results with the experimental results. The compared results of velocity field, temperature distribution, and pressure field distribution were shown in Table II.

TABLE II.

RESULTS COMPARED

	Temperature of inlet/outlet (K)	Pressure of inlet/outlet (MPa)	Velocity of inlet/outlet (m/s)	Mass flow of inlet/outlet (kg/hr)
Simulation results	-111.15/271.3	10/0.91	2.76/3.14	190/190
Experimental results	-111.15/276	10/0.96	2.5/2.96	181/183

A. Temperature Distribution Law

LNG got into the rib-tube from the bottom rising to absorb heat from sea water which flow down along the outside wall, and changed to NG when the temperature reached to its transformation temperature. The endothermic process continues until exit at the top of the rib-tube. The temperature distribution of the symmetric surface of the heat transfer tube was shown in Fig.5. According to this Figure, we could conclude that the temperature at the bottom of rib-tube was lowest and it evenly increment along rib-tube , and the temperature of LNG in the annular gap rise faster than that in the inner tube, which could continue heat the LNG in the casing; this structure was conducive to improve the efficiency of the gasification happening in the tube; the temperature gradient along entire rib-tube changed gradually, which could guarantee the desired stable heating process.
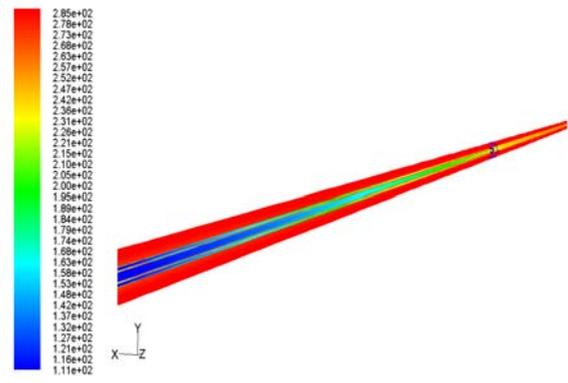

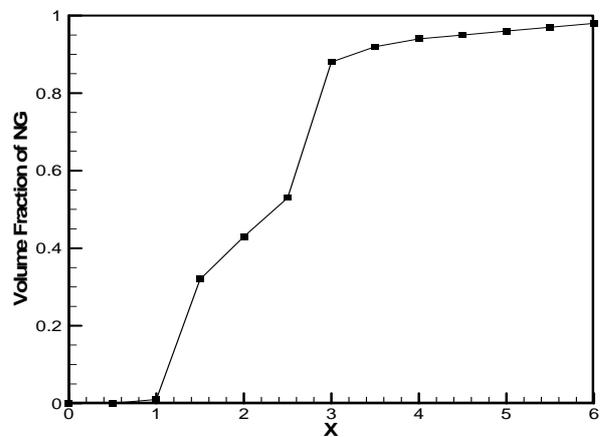Fig. 5: Temperature distribution contours on symmetry plane of rib-tube

Fig. 6: Gas fraction rule in the cross-section of rib-tube

B. Gas Component Distribution Law

"DEW POINT" is the beginning temperature as a critical point that medium changes from liquid phase to gas phase.

Fig.6 gave the average gas fraction rule in the cross-section of rib-tube, from which we could see that the gasification process continuously enhanced along the rib-tube, and it was consistent with the trend described above. As the temperature rising, gasification enhanced, and gas fraction was increasing. Because of the high operating pressure and high transformation temperature, LNG need a certain time to absorb enough heat, the gasification would not begin until the temperature reached the transformation temperature. Because all of the reasons above, the gas fraction between inlet and 1.5m length was almost 0. According to the gas fraction contour shown in Fig.7 corresponding to Fig.6, we could also see that a length between 2m to 3m contained a region in which the gas fraction zoomed quickly, and it indicated that fluid blended vigorously in the junction of the evaporator section and heating section, which enhanced the gasification process, leading to the total gas rate rising fast[7]. Fig.8 showed that the gas fraction in a distance of the middle of rib-tube, near the top, the temperature distribution tended to be uniform, and the gas fraction was basically saturated.
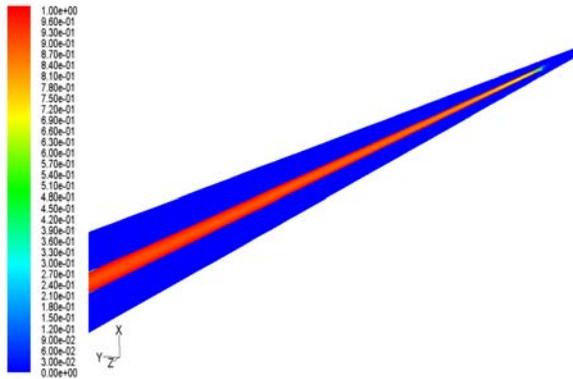
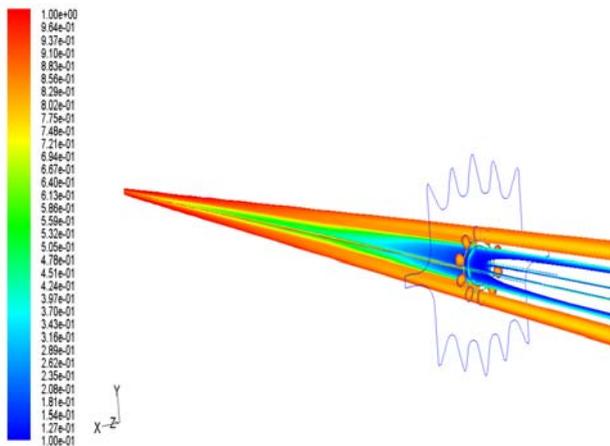Fig.7: Gas fraction rule in the cross-section of rib-tube

Fig. 8: Gas fraction rule in the middle of the rib-tube

In order to more clearly observe the gasification process, different cross-sections were chosen to obtain the gas fraction shown in Fig.9-1 to Fig 9-4.The gas fraction near the exit is 0.987.
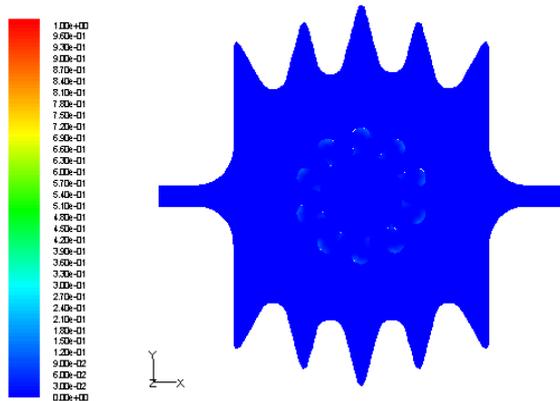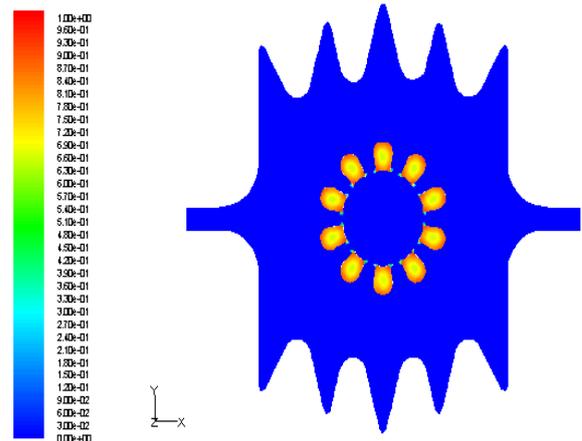

Fig.9-1: NG volume fraction at section Z=1m
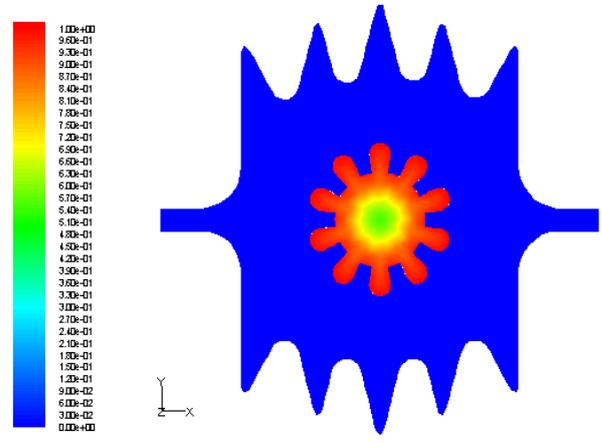

Fig.9-2: NG volume fraction at section Z=2m

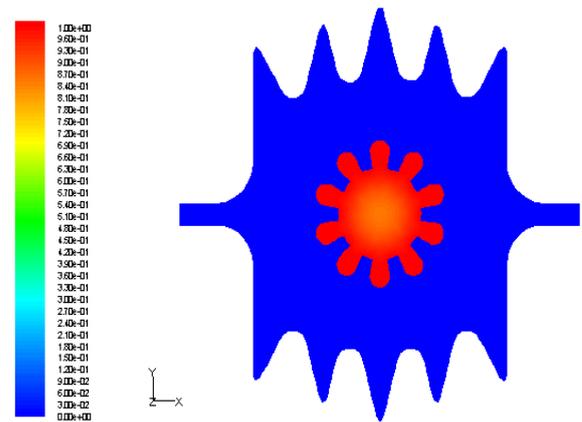Fig.9-3: NG volume fraction at section Z=3m

Fig.9-4: NG volume fraction at section Z=6m

C. Velocity Field Distribution Law

Fig.10 was the velocity contours of symmetry plane of rib-tube. According to the temperature and gas rate distribution, with the continuous generation of gas-phase, the velocity of mixture increased significantly and significant speed differed between the two phases exist, because that NG generating-speed was much higher than LNG. Therefore, the velocity of the mixture increased and reached to a maximum at the top from the bottom to

the top of rib-tube[8,9]. According to Fig.11, we could see that in the middle of the rib-tube, flow in the annular gap and in the inner tube blended, two-part fluid combined and downstream speed was consistent with the gasification process ongoing, the generated gas continuously incorporated into the mixture, so that the mixture velocity was increasing.
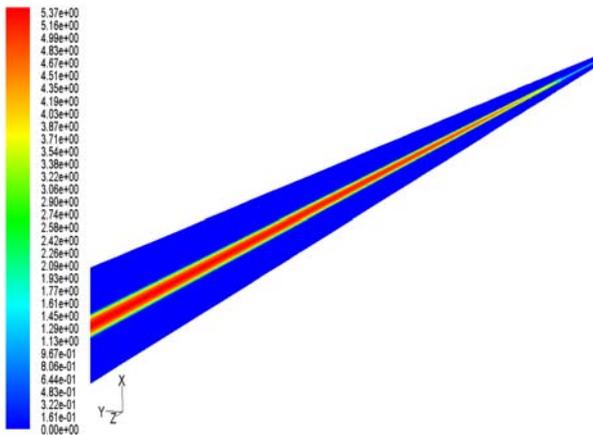

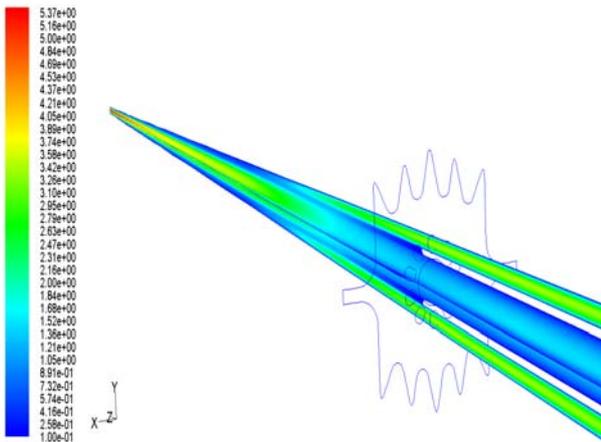Fig.10: Velocity distribution contours on symmetry plane of rib-tube

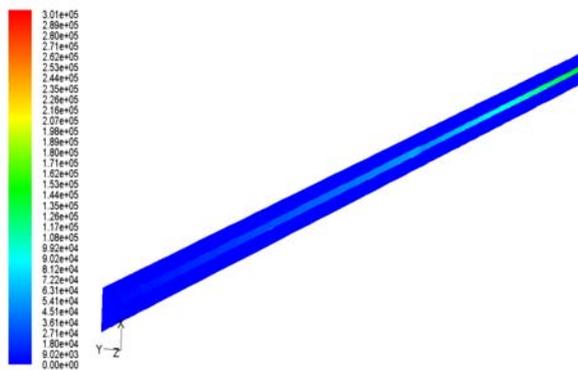Fig.11: Velocity distribution contours in the middle of rib-tube

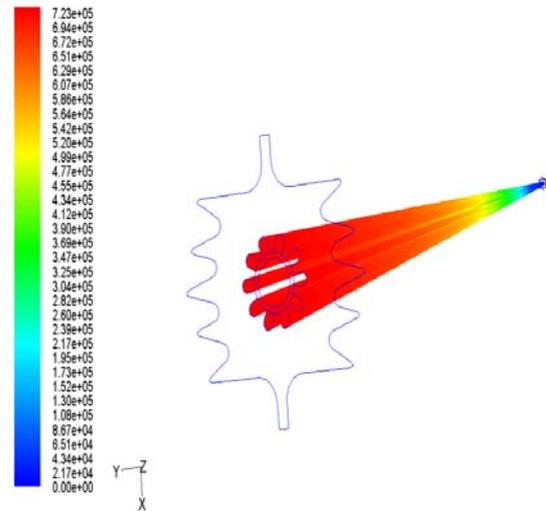Fig.12: Pressure distribution contours on symmetry plane of rib-tube

Fig.13: Pressure distribution contours in the inner wall surface of rib-tube

D. Pressure Field Distribution

Fig.12 was the pressure distribution, from which, we could conclude that pressure gradually reduced along rib-tube. There were two reasons for this phenomenon: firstly because of the complex shape with an inner casing structure in rib-tube, the pressure lost more along the way than the light pipe; secondly, with the gasification process going on, the gas constantly generated, and its speed increased, the pressure loss was also growing. Fig.13 showed that a uniform pressure variation of the inner surface changed gradually, which was consistent with the fact.

VI. CONCLUSIONS

Flow and heat transfer were complex process on ORV, according to the model in this paper, based on theoretical analysis and experimental results, the following conclusions could be obtained:

(1) As could be seen by the temperature, the temperature at the bottom was lower and rise gradually along rib-tube, the temperature of LNG in the annular gap rising faster than that in the inner tube, which could continue heat the LNG in the casing, and this structure was conducive to improve the efficiency of the gasification.

(2) As the temperature rising, gasification was enhanced, and gas fraction was increasing. In the junction of the evaporator section and heating section, fluid blended vigorously, which enhanced the gasification process, leading to the total gas rate rise fast.

(3) With the continuous generation of gas-phase, the velocity of mixture increased significantly and significant speed differed between the two phases exist, in the middle of the rib-tube, flow in the annular gap and in the inner tube blended, two-part fluid combined and downstream speed was consistent with the gasification process ongoing, the generated gas continuously incorporated into the mixture, so that the mixture velocity was increasing.

(4)With the gasification process going on, the gas

constantly generated, and its speed increased, the pressure loss was also growing. A uniform pressure variation of the inner surface changed gradually.

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