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Three dimensional numerical (3D CFD) study of effect of pressure-outlet and pressure-far-field boundary conditions on heat transfer predictions inside vortex tube

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ABSTRACT

A vortex tube can be used as a heating device for preheating the pipes inside a solar heater. A vortex tube usually has some parts such as: A vortex-chamber, one or more inlet nozzles, a cold end orifice, a control valve at hot end and a working tube. The vortex-chamber is a main part of vortex tube which the pressured gas is injected into this part tangentially. An appropriate design of vortex-chamber's geometry leads to better efficiency and good performance of vortex tube. In this study, the computational fluid dynamics (CFD) model is created on basis of an experimental model and is a three-dimensional (3D) steady compressible model that utilizes the k-ε turbulent model to solve the nonlinear flow field equations. In this study a comparison between usage of two different boundary conditions (Pressure-Outlet and Pressure-Far-Field) has been presented. The results show that there is no essential difference between these two boundary conditions for heat transfer predicting inside a vortex tube separator. So, the scientists which work on numerical aspects of vortex tubes and have no access to the experimental data can use the Pressure Far Field boundary condition.

1. INTRODUCTION

In fact the first version of this device (vortex tube) was explored or invented based on an accidental investigation (by Ranque [1]). Several years later a German scientist [2] directed his efforts on improving this amazing device and vortex tube was introduced academically for the first time in 1947. As seen in Fig. 1, a vortex tube includes different parts such as: one or more inlet nozzles, a vortex-chamber, a cold end orifice, a throttle valve that is located at the end of main tube and a working tube. When pressured fluid is entered into the vortex-chamber tangentially via the nozzles, a strong rotational flow field is created. When the fluid tangentially swirls to the center of the vortex tube it is expanded and cooled.

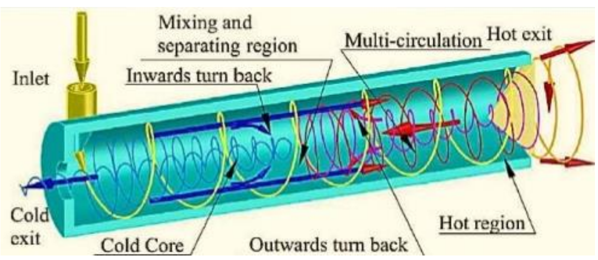


Figure 1. A schematic drawing of Ranque-Hilsch vortex tube

After occurrence of the energy separation in the vortex tube the pressured inlet fluid stream was divided into two different fluid streams including hot and cold exhaust fluids. The "cold exit or cold orifice" is located at near the inlet nozzles and at the other side of the working tube there is a changeable stream restriction part namely the control or throttle valve which determines the mass flow rate of hot exit. a percent of the compressed gas escapes through the valve at the end of the working tube as hot stream and the remaining gas returns in an inner swirl flow and leaves through the cold exit orifice. Opening the throttle valve reduces the cold airflow and closing the valve increases the cold mass flow ratio. Some of investigations on various aspects of vortex tubes are briefly mentioned below. Dutta et al. [3] performed a numerical study on energy separation inside a simple vortex tube. In their work a three dimensional Computational Fluid Dynamics (CFD) model is applied to study the phenomena of energy separation in a vortex tube with compressed air at normal atmospheric temperature and cryogenic temperature as the working fluid. Also in this work the NIST real gas model is employed for the first time to accurately compute the thermodynamic and transport properties of working fluid inside the vortex tube. Mohammadi et al. [4] carried out an experimental study to optimize the vortex tube parameters. In their study, a simple vortex tube with various parts is employed to obtain the optimum nozzle intake numbers and diameter. The influence of inlet pressure and cold mass fraction are also studied. Results illustrate that increasing the nozzle numbers causes a temperature drop and the optimum nozzle diameter corresponds to quarter of working tube diameter. The heat and mass transfer between the cold and hot cores (inside the vortex tube) is analyzed by Rafiee and Sadeghiazad [5]. The capabilities of different turbulence models (the RSM, LES, *k–ω, k–ε* and *SST k–ω)* for predicting the flow structures within the air separator were examined by Baghdad et al. [6] and Rafiee and Sadeghiazad [7]. Rafiee and Rahimi [8] studied the thermal performance of vortex tubes with different inlet temperature. Pourmahmoud et al. [9] analyzed the effect of shell heat transfer on vortex tube performance. Pourmahmoud et al. [10] determined the optimum value for the length of vortex tube. Some variations in the temperature drops are seen when a bended main tube is used in the structure of the air separator. These variations are reported in comparison with the air separator equipped with the straight main tube [11]. The effect of divergent main tube has been investigated by Rahimi et al. [12] and the optimum angle for the divergent main tube has been achieved numerically. Some factors regarding the vortex tube structure (the inlet of slots, the ratio of slots, the hot and cold exit area, the rounding off edge radius, the internal radius of main tube and the convergent slots) were optimized by Rafiee et al. [13], Rafiee and Sadeghiazad [14] and Pourmahmoud et al. [15]. Some refrigerant gases (R728, R32, R134a, R161, R744, and R22) have been examined in the vortex tube air separator and the thermal performance of air separator has been studied and the best refrigerant gas has been determined [16-17]. Rafiee and Sadeghiazad [18] analyzed the effect of different boundary conditions (pressure outlet and pressure far field) at the outlets and different working gases on the energy separation inside a vortex tube. Rafiee and Sadeghiazad [19-20] managed some experimental setups to optimize the control valve structural parameters such as the conical angle and the cone length and proved that there are some optimized values which lead to the best thermal capability. The impact of a new shape of the hot tube (the convergent main tube) is experimentally tested by Rafiee et al. [21] and Rafiee and Sadeghiazad [22-26]. Their results stated that there is an optimized angle for the convergent main tube to produce the best cooling capacity. Rafiee and Sadeghiazad [27] proposed a new energy explanation to analyze the thermal distribution and the exergy density inside the air separator applying the measured flow factors along the hot tube. The thermophysical parameters inside the vortex tube are comprehensively reported by Rafiee and Rahimi [28]. A comprehensive study was done to analyze the isotope separation using vortex tubes by Lorenzini et al. [29]. The effect of shape of control valve is analyzed by Rafiee and Sadeghiazad [30]. The effect of inlet temperature on the VT performance is evaluated by Pourmahmoud et al. [31]. Vortex tubes can help to separate the articles from the air. The air climate and related energy is investigated by Alberto Mirandola and Enrico Lorenzini [32].

2. BASIC CONCEPTS

The performance measurements on the VT systems (usually) are pointed and presented based on the temperature differences (there is no difference what kind of the VT is used, RHVT, PVT). There are three definitions; first, the cold temperature difference or ΔT_{cold} (difference between cold and inlet sides), the total temperature difference or ΔT (difference between cold and hot sides) and the hot temperature difference or ΔT_{hot} (difference between hot and inlet sides), these definitions are as bellow:

$$\Delta T_h = T_h - T_{inlet} \tag{1}$$

$$\Delta T_C = T_{inlet} - T_C \tag{2}$$

3. PHYSICAL MODEL DESCRIPTION

The 3D CFD model is created on basis of that was used by Skye et al. [33] in their experimental (Fig. 2) work. It is noteworthy that, an Exair^{TM} 708 slpm vortex tube was used by Skye et al. [33] to perform all tests and to take all of the experimental data. The dimensional geometry of this vortex tube has been summarized in the Tab. 1. The 3D CFD mesh grid is shown in Fig. 3. In this model a regular organized mesh grid has been used. All radial line of this model of meshing has been connected to the centerline and the circuit lines have been designed organized from wall to centerline. So, the volume units that have been created in this model are regular cubic volumes. This meshing system helps the computations to be operated faster than the irregular and unorganized meshing, and the procedure of computations have been done more precisely.

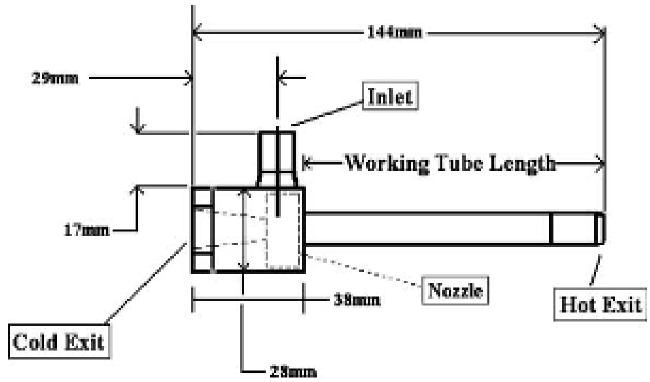
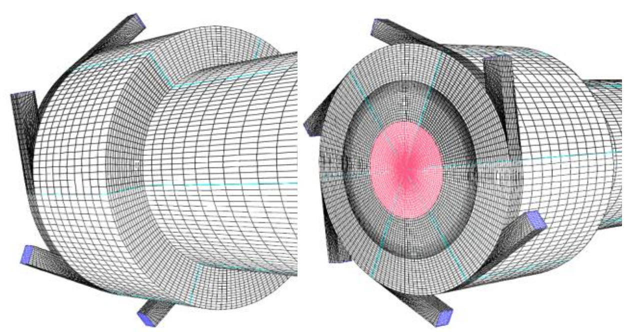


Figure 2. Schematic of vortex tube that used by Skye et al.

Table 1. Geometric measurements of the vortex tube that was used by Skye et al. [33]

Measurement	Value
Working tube length	106 mm
Nozzle height	0.97 mm
Nozzle width	1.41 mm
Nozzle total inlet area (An)	8.2 mm^2
Cold exit diameter	6.2 mm
Cold exit area	30.3 mm^2
Hot exit diameter	11 mm
Hot exit area	95 mm^2

For this reason the CFD model has been assumed a rotational periodic condition. Hence, only a sector of the flow domain with angle of 60° needs to consider for computations as shown in Fig. 3.



(a) (b)

Figure 3. a and b) 3D CFD model of vortex chamber with six straight nozzles

4. RESULTS AND DISCUSSION

In this section, the purpose is to demonstrate this claim which there is no difference between the pressure-far-field boundary condition and pressure-outlet boundary condition. As seen in Figure 4 and 5 cold exit temperature and hot exit temperature at both boundary conditions have good agreement with each other (in this section, reports are based on contours data).

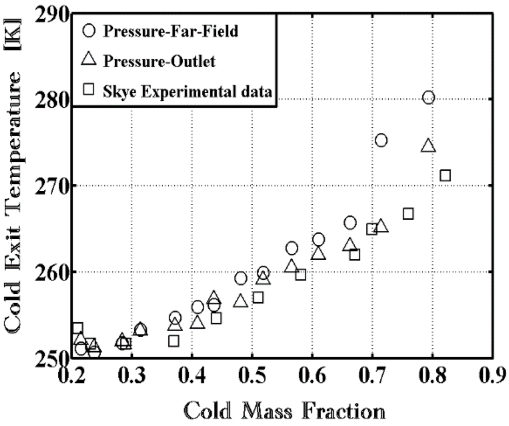


Figure 4. Cold Exit Temperature: comparison of two boundary condition(pressure-far-field and pressure-outlet) and experimental data

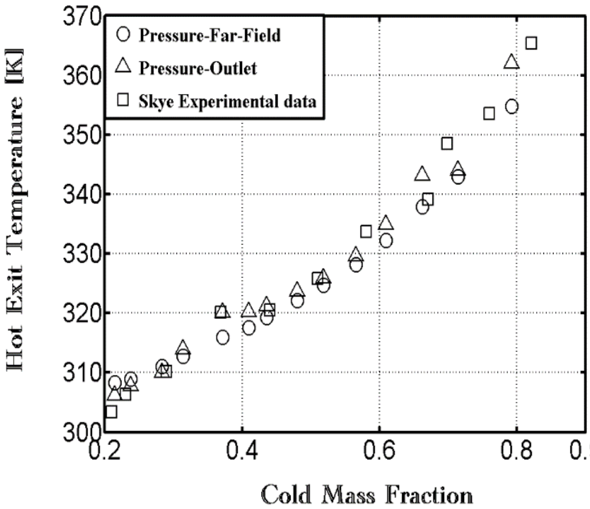


Figure 5. Hot Exit Temperature: comparison of two boundary condition(pressure-far-field and pressure-outlet) and experimental data

In Fig. 4 the cold temperature of gas which exits from cold exhaust has been compared in three states as function of cold mass fraction, including: experimental data, setting pressure-far-field boundary condition and setting pressure-outlet boundary condition. As seen in Fig. 5 the hot exit temperature has been illustrated as function of cold mass fraction in three mentioned states.

Some parameters such as axial velocity, tangential velocity, total pressure and total temperature at three sections (Z/L=0.1, 0.4 and 0.7) of the working tube have been studied as a function of dimensionless radial distance (r/R), meanwhile the total temperature on the wall of vortex tube has been investigated as a function of dimensionless length (Z/L) of working tube. Fig. 6 and 7 shows axial velocity and tangential velocity of fluid inside the working tube in three mentioned section respectively which have been obtained at different dimensionless radial distances. This Figure illustrates a comparison form of CFD results with employing two different boundary conditions.

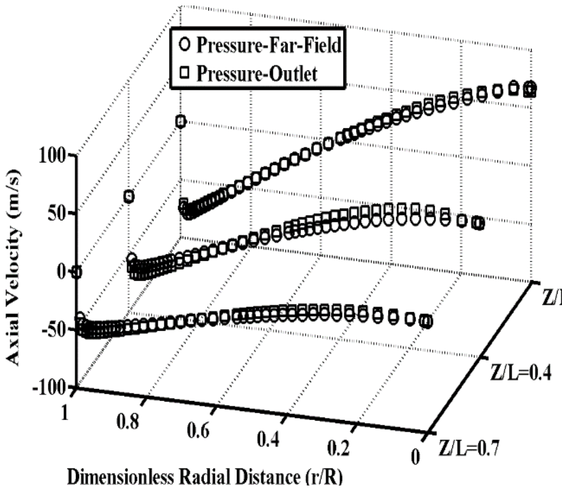


Figure 6. Axial Velocity: indication of axial velocity at three section (Z/L=0.1, 0.4, 0.7)

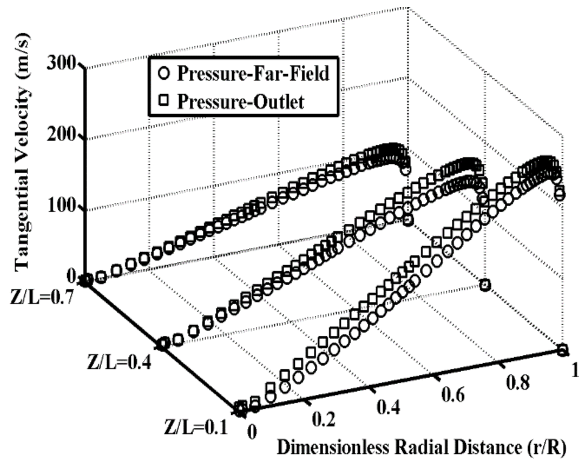


Figure 7. Tangential Velocity: indication of tangential velocity at three section (Z/L=0.1, 0.4, 0.7)

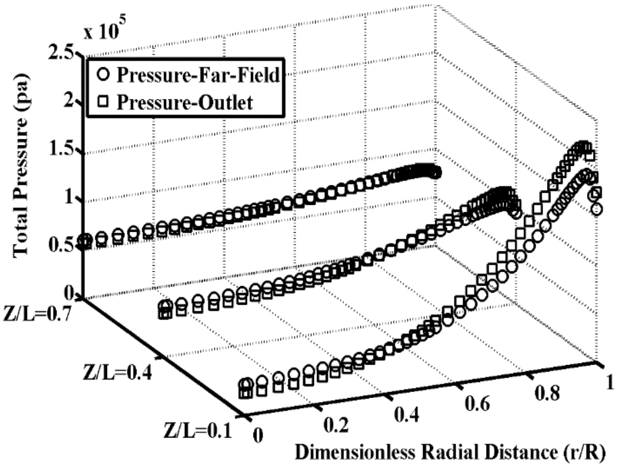


Figure 8. Variation of total pressure at three section (Z/L=0.1, 0.4 and 0.7)

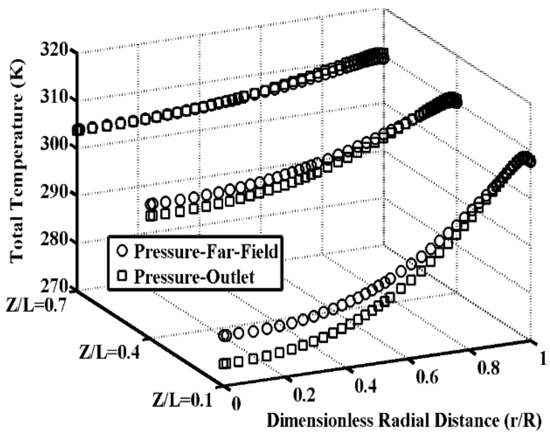


Figure 9. Changing in total temperature pressure at three section (Z/L=0.1, 0.4 and 0.7)

The variation of total pressure and total temperature for different value of dimensionless radial distances at three sections (Z/L=0.1, 0.4 and 0.7) of working tube has been shown in Figure 8 and 9 respectively.

The total temperature results on working tube have been shown in Fig. 10. This Figure indicates the variation of total temperature on wall at pressure-far-field boundary condition and pressure-outlet boundary condition in comparison form.

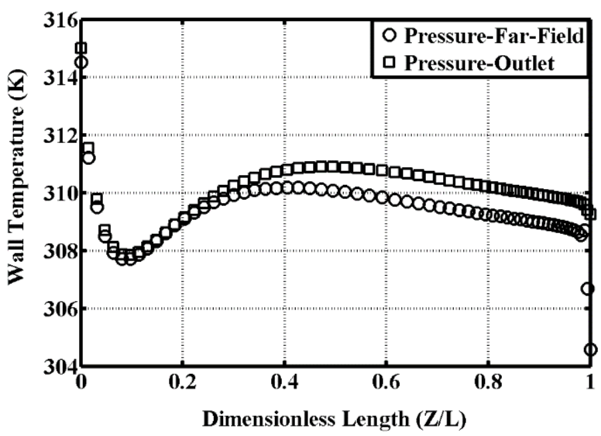


Figure 10. Comparison between the results of pressure-far-field boundary condition and pressure-outlet boundary condition on the wall of working tube

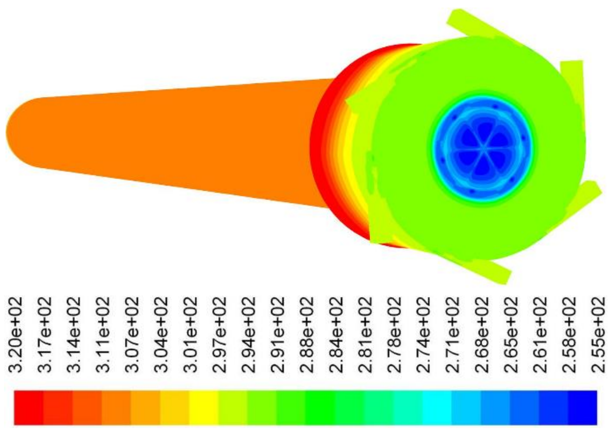


Figure 11. Total temperture of a vortex tube with pressure far field boundary condition

where, in Fig. 10, Z/L represents the dimensionless length of the vortex tube. With these validations, this theory has been demonstrated that there is no difference between pressure-far-field boundary condition and pressure-outlet boundary condition. Hereinafter the CFD researchers that haven't the pressures at exhausts of vortex tube can do their predictions. By employing this method, having the pressures at exits is not important but knowing the information about vortex tube geometry and conditions of inlet gas is necessary. Figure 11 shows the total temperature contour for a vortex tube using Pressure-Far-Field boundary condition.

5. CONCLUSIONS

An optimization model of vortex-chamber has been modeled in this paper. We developed a 3D computational fluid dynamic model to simulate a vortex-chamber of vortex tube. Some changes have been implemented on boundary conditions and the effect of these changes has been studied to achieve the better performance of vortex tube. Primitive results have been validated with Skye *et al.*'s experimental data and show a good agreement with these results. This research shows that the pressure-outlet boundary condition can be replaced by pressure-far-field boundary condition and pressure-far-field boundary condition is as same as pressure-outlet boundary condition.

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