Numerical study on the effects of conical angle on the performance of a vortex tube

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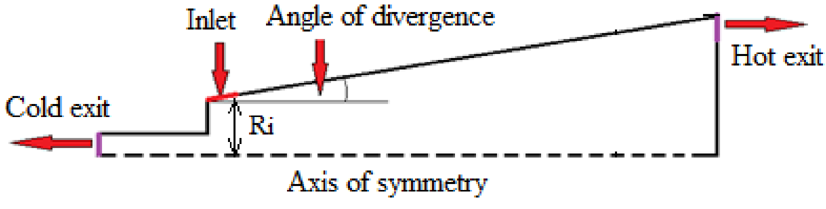
Abstract:
The objective of this research paper is to optimize the performance of a counter flow vortex tube. The vortex tube (VT) is a device that splits the inlet compressed gas into two lower pressure streams of exit gases, one stream warmer than the inlet stream while the other colder than the inlet stream. As, thermal separation inside the device is caused by the generation of vortex flow and pressure is the only energy available at the inlet, therefore, geometry of the device plays an important role in the process of temperature separation. The performance of the tube is studied with three different configurations of the vortex tube such as parallel, convergent and divergent tube. Simulations are carried out using standard k-epsilon model. The results obtained from the numerical analysis reveals that the convergent body type vortex tube produces better cooling effect than the parallel and divergent tube.

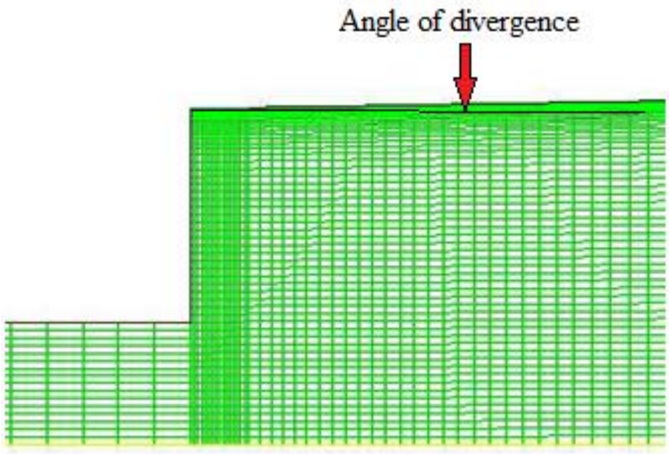
Key words: Standard k-epsilon model, Conical angle, Cooling effect, Vortex tube

Introduction
The vortex tube (VT) is a device that splits the inlet compressed gas into two lower pressure streams of exit gases, one stream warmer than the inlet stream while the other colder than the inlet stream. This phenomenon of splitting the inlet gas into two streams of different temperature is referred as temperature or energy separation. It is used as a gas purifying device when the exit gases are of different gas purities. So, the properties of the exit gases such as temperature, pressure, gas purity, density etc. are controlled as per the requirements of the job to be done. The simplicity of fabrication and low cost of maintenance have led to a resurgence of research on vortex tube.

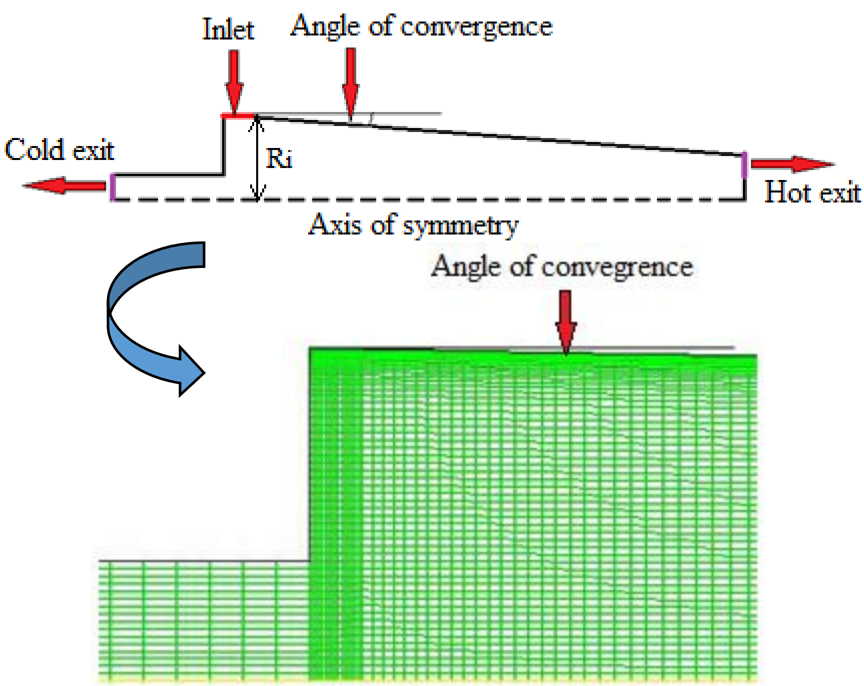
The literature on the effects of various geometrical parameters of a RHVT reveals that a divergent type vortex tube produces higher thermal separation as compared to a straight tube. Though a good number of studies on divergent vortex tube are available in literature the results reported differ significantly from each other and consequently, no concrete conclusions could have been drawn from these.

Numerical Model
The schematics of divergent and convergent vortex tubes are shown in Fig. 1. The dimensional values of the vortex tube geometry are similar to that of straight tube used by [Shannak, 2004] in his experimental work. Other geometrical details of the vortex tubes are as follows. The angle of divergence or convergence is taken 2^o, the tube $L/D = 10$, the cold and hot exit widths are taken respectively as 1.8 mm and 0.8 mm and the inlet width is 0.8 mm. The computational grid consists of 16,096 cells for both the vortex tubes. Since a grid independence study with straight tube is already carried out and reported in [Bej and Sinhamahapatra, 2016], no additional study is carried out in this regard.





(a)



(b)

Fig.1: Schematics of vortex tube geometry (a) divergent vortex tube, (b) convergent vortex tube

Results and Discussion

1. Effects of conical angles on swirl velocity profiles

The growing interest in the process of thermal separation in a vortex tube has created a need for better understanding of the relevant flow features. A reasonable starting point in this direction is the analysis of swirl velocity distribution. Fig. 2 depicts the radial distribution of swirl velocity at three different axial locations, namely x/L = 0.15, 0.56, and 0.98. The swirl velocity profiles for the straight and conical tubes near the inlet (x/L = 0.15) are quite similar to each other as the flow in each case is subjected to identical boundary conditions at the inlet and the cross sectional areas at this location are nearly equal. However, the profiles here still indicate that the swirl velocity is marginally higher in the convergent tube but slightly smaller in the divergent tube in comparison with the straight tube. On moving towards the hot exit (*x/L* = 0.56 and 0.98), the swirl velocity in the convergent tube is found to be considerably higher over the straight tube. The swirl velocity in the diverging tube is the smallest. The swirl velocity gradient follows the same trend with the converging tube having the largest gradient and the diverging tube having the smallest gradient. The straight tube takes an intermediate place between the convergent and divergent tubes. The larger swirl velocity gradient along the radial direction causes increased work transfer due to tangential shear. Consequently, higher thermal separation is achieved in convergent tube compared to the straight and divergent tubes.

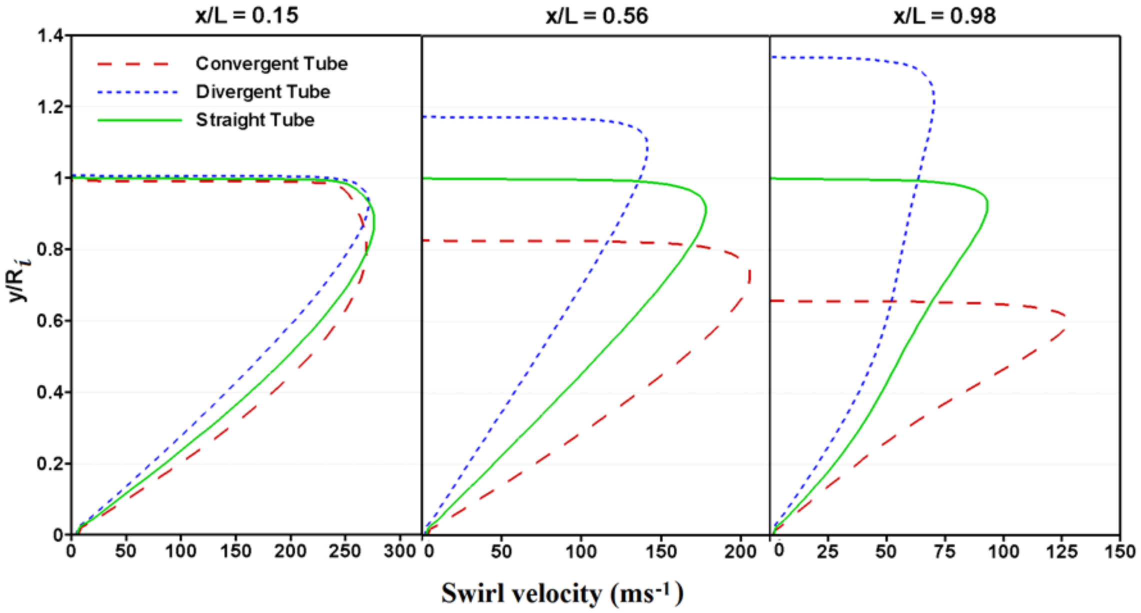


Fig. 2: Radial distribution of swirl velocity profiles in conic and straight tube, ξ= 0.5

2. Effects of conical angles on static pressure profiles

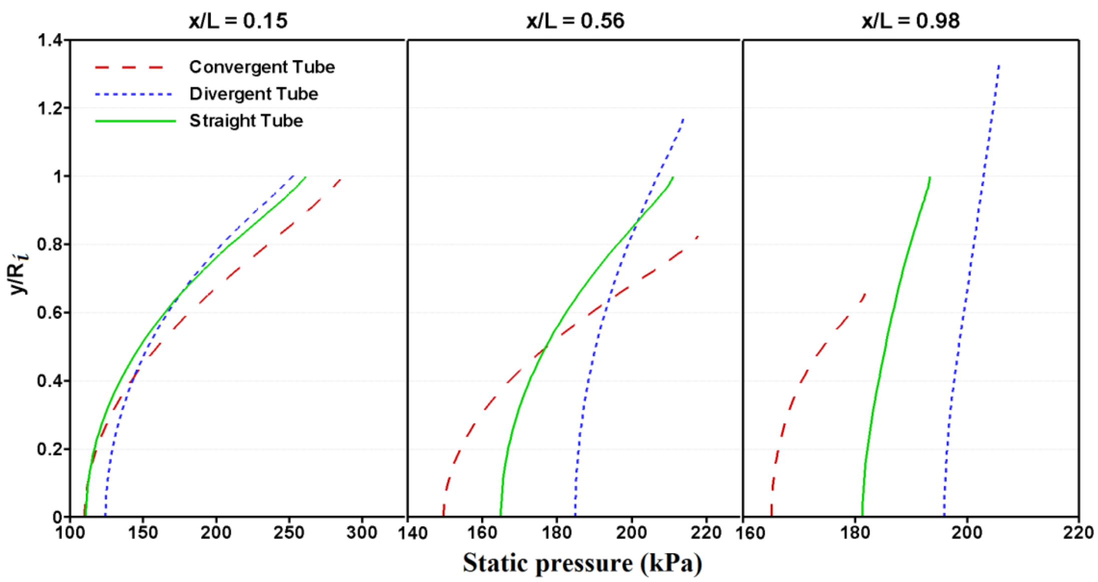


Fig 3: Radial distribution of static pressure profiles in conic and straight tube, ξ= 0.5

The radial distributions of static pressure in the convergent, divergent and straight tubes are presented in Fig. 3 at three different axial locations, namely at x/L = 0.15, 0.56 and 0.98. At the station near inlet (x/L = 0.15) the effect of the convergence or divergence of the tube is practically small and the flow features are quite similar in the three tubes. However, it can still be seen that the pressure gradient in the convergent tube is increased a little, while it is decreased marginally in the divergent tube. With increase in x/L the radial pressure gradient in the convergent vortex tube increases significantly as the pressure in the central core decreases markedly. The pressure gradient in the divergent vortex tube is smallest amongst the three. There is hardly any expansion in the central zone in the divergent tube. The radial pressure gradient leads to momentum transfer from the axial zone to the peripheral region of the vortex tube. Increase in the static pressure gradient causes more momentum transfer and hence, higher thermal separation. Thus, the static pressure profiles confirm higher thermal confirm higher thermal separation in the convergent tube than in the straight and divergent tubes.

3. Temperature Separation

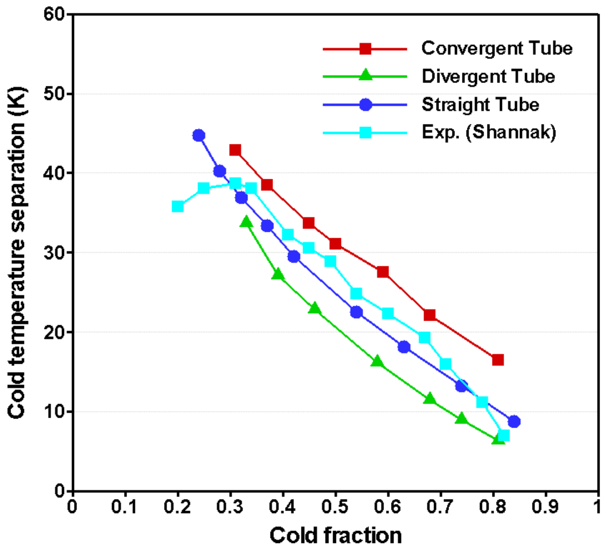


Fig. 4: Cold temperature separation in straight and conic tubes

As vortex tube is a device meant for generation of thermal separation, therefore, the performances of the tubes are assessed on the basis of cold, hot and total temperature separations. The numerically predicted cold temperature separation in the straight tube is compared with the experimental data due to Shannak (2004) to validate the simulations. Fig. 4 depicts the cold temperature separation obtained in the straight, divergent and convergent vortex tubes. The experimental data Shannak (2004) is also plotted in this figure for comparison. It is clearly evident from Fig 4 that the cold temperature separation in the straight tube predicted by the present numerical model agrees quite well with the experimental data. The reliability of the model is thus reconfirmed. Some discrepancies at the lower values of cold fractions are observed where the experimental data shows a fall in the cold separation. However, this could not be resolved.

The figure also reveals the influence of 2° divergence/convergence of the tube on the cold separation. To compare the influence of conical angle on the performance all other computational and geometrical parameters are kept same as in the straight tube. The results show that vortex tube with angle of convergence of 2° performs the best amongst the three tubes studied here. The improvement in cooling performance achieved by the convergent tube is about 5 - 8 K. On the other hand, the divergent vortex tube performs the worst. This observation made by us contradicts to the results reported by Gulyaev (1966), Takahama and Yokosawa (1981), Pouraria and Zangooee (2012), Guen et al. (2013). The present numerical study is in agreement with the findings of Behera (2011). However, a divergent vortex tube of 2° angle of divergence was used by Crocker et al. (2003) to improve the air separation capabilities of a two-phase flow. An improvement in two-phase flow separation due to divergent vortex tube was also reported by Behera (2011). The hot temperature separation and total temperature separations also demonstrate better performance due to convergent vortex tube as compared to divergent and straight tubes as shown in Fig. 5 and Fig. 6 respectively. It is observed that the differences in the performances among the vortex tubes increase with the cold fraction

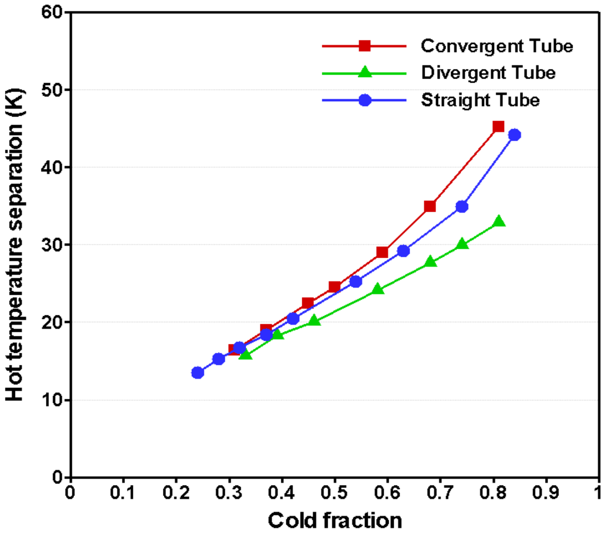


Fig 5: Hot temperature separation in straight and conic tubes

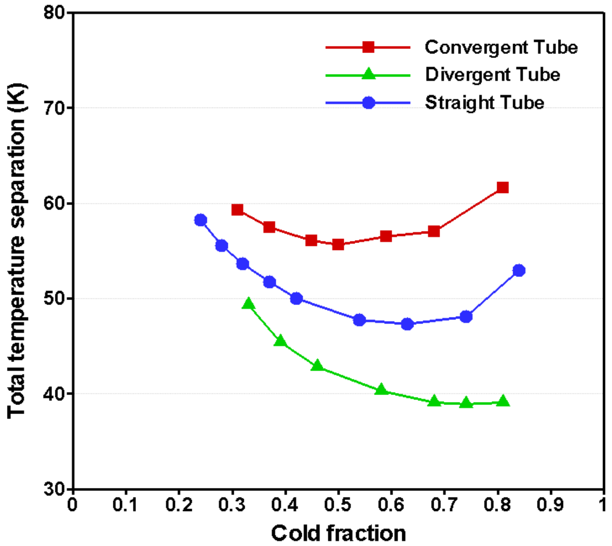


Fig 6: Total temperature separation in straight and conic tubes

Concluding remarks

Based on computed cold, hot and total temperature separations, the convergent tube produces highest thermal separation as compared to straight and divergent tubes. According to Gulyaev (1966), Takahama and Yokosawa (1981), Chang et al., (2011), Pouraria et al. (2012) divergent tube improves the temperature separation. Crocker et al. (2003) used a divergent vortex tube of 2° angle of divergence to improve the air separation capabilities of a two-phase flow. Behera (2011) has also found some improvement in species separation due to two-phase flow in divergent vortex tube. However, Behera

(2011) found no improvement in thermal separation. The present numerical study is in agreement with the findings on thermal separation due to Behera (2011). Detailed parametric studies are necessary to confirm the performances of diverging vortex tube.

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