Experimental Analysis on Heat And Mass Transfer and Separation Process Inside A DCVT Based on Pressure Distribution

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The types of vortex tubes (VTs) or air separators (professional separating, heating and cooling systems used in large engines like submarines, ships and etc) are usually determined based on the position of cold and hot exit areas. Based on these arrangements, there are three general types of vortex tubes including; Ranque-Hilsch (opposite directions), Parallel (same direction) and Double-Circuit (opposite directions with an extra injection at the center of hot valve). This study tries to present a comprehensive study on Double-Circuit vortex tube (DCVT). In this study the impact of pressure ratio (extra injection pressure/inlet pressure) on the separation quality is investigated. Based on the experimental results there are optimum values for the nondimensional pressure (P_{ex}/P_{in}) equal to and 0.2.

1. Introduction

Double-Circuit vortex tube (DCVT) is a special type of vortex tube which applies an extra inlet mass flow at the center of the throttle valve on the hot end of the main tube (Figure 1, Alekhin et al., 2015). The first vortex tube was invented (completely in an accidental research) by Ranque (1933), after that this device was introduced and improved academically by Hilsch (1947) in several years later. After these two steps (the invention and the first improving), three types of this device are introduced as said before and the researches are continued on improving of the thermal performance of vortex tubes. Figure 2 shows the experimental setup of this study on the DCVT.

It can be said that there is a huge volume of papers on the RHVT and its performance despite severe lack in scientific reports on the DCVTs and PVTs. Here we want to present a brief review on the RHVT studies. Rafiee and Sadeghiazad (2017 and 2017a) designed a numerical or CFD method (based on DCVT model) for describing the interaction phenomenon between the flow and energy patterns in a DCVT. Sometimes there

Figure 1: 1-main inlet nozzle; 2-energy separation chamber; 3-diffuser of cold flow; 4-nozzle of additional flow

Figure 2: Schematic diagram of experimental setup

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are some requests for special RH vortex tubes with indirect outputs (with the desired angles). So, industry needs the curved RHVTs with special angles. The details of the thermal efficiencies regarding the curved vortex tubes have been described based on different curvature angles by Rafiee et al., (2016). Dincer (2011) managed three innovative arrangements of the vortex tubes systems as the six RHVT cascade types, three-fold VT and the conventional VT considering different operational pressures. As said before, a vortex tube (convergent VT) has some essential structural parameters such as the main length for hot tube, the orifice diameter for exhausts and etc; these parameters are optimized in an experimental investigation by Rafiee and Sadeghiazad (2016a; 2016b; 2016c; 2017b; 2017c; 2017d) and Rafiee et al. (2015). The effect of geometrical factors of straight VT is analyzed by Rafiee and Sadeghiazad (2014a; 2015; 2016d; 2016e; 2016f; 2016g), Pourmahmoud et al. (2014) and Rafiee et al. (2013). The interaction between the gas layers can be affected by the molecular weight, so, the type of operational fluid can be considered as an effective parameter on the thermal performance of a vortex tube, this effect is analyzed by Han et al. (2013), Thakare and Parekh (2015) and Pourmahmoud et al. (2013) via some gases such as R728, N2, O2, R161, CO2, R32, R134a, R744, and R22. Rafiee and Rahimi (2013) focused on increasing the thermal separation efficiency of a RHVT via designing a new type of nozzles. They named this kind of nozzles as convergent nozzles and introduced a nondimensional parameter to define the correct way for using this kind of nozzles. As we know, the aim of all researches on optimization of the structural parameters for a vortex tube is enhancing the thermal capability of this device which leads to decreasing the costs in related industries. Beside the conventional methods, there are some different analyzing methods (such as "exergy considering", (Saidi and Aliaf Yazdi, 1999; Ouadha et al., 2013; Rafiee and Sadeghiazad, 2014b) which can be considered as useful tools to accompany the old methods for optimizing the device (VT). The nozzle or injection slot has an internal diameter based on its shape. The effect of this matter is reported by Aydin and Baki (2006). There are some researchers which added a divergent main tube on their VT systems and reported different (sometimes opposite) results Rahimi et al. (2013) reported an optimum angle for the best efficiency, but, Chang et al., (2011) reported that the divergent tube destroys the separation in the VTs). Some researchers determined the CFD solution ways in their works Rafiee and Rahimi (2014) and Akhesmeh et al. (2008) by 3D models. Increasing the rotational speed can lead to the better separation, this matter can gain by applying the convergent nozzles reported by Pourmahmoud et al. (2012). Moraveji and Toghrail (2017) analyzed the effect of nozzle number, tube length and cold orifice diameter on VT performance using methane as working fluid.

2. Experimental process

In all VT types, the operating gas source is the pressurized gas supplied by a compressor or a high pressure cylinder (the pressure range is between 2 to 10 bar). The temperatures are recorded by a data logger (Center R 309 with 4 output channels, Range -200 C to 1370 C, Resolution 0.1 C) in all lines (main inlet, extra inlet, cold and hot exhausts for the DCVT). In the designed VT, the slots are set on a ring coupled on the entrance of the main tube (6 slots) with thermal welding. The pressure at the hot, cold, inlet and extra inlet is considered by the analog pressure gages. The rate of gas (air) is under control by the rotameters in all lines. In RHVTs we need a simple control valve without any complicated structures (just a conical shape with a certain angle and diameter at the end), but the situation is a little different in the case of DCVTs. In this kind, we need to apply a special valve with an orifice at the center of the valve (this orifice conducts the extra air to the main tube in the case of DCVT). Fig. 2 can help readers to imagine the general shape of this kind of control valve. The pressure fluctuations are controlled by a regulator on the line, so, we have a stable pressure at the inlets. Also, this setup can present any exact cold mass fractions, because of the valve's actions on the rotameters (in all lines). We adjusted the pressure at the inlet line by a valve on 1 MPa. The set-up is working (continually) for 10 to 15 minutes in each case to reach a stable condition (after adjusting the pressure at the inlets).

3. 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 or DCVT). There are three definitions; first, the cold temperature difference or $\Delta T_{\text{cold}}$ (difference between inlet and cold sides), the total temperature difference or $\Delta T$ (difference between hot and cold sides) and the hot temperature difference or $\Delta T_{\text{hot}}$ (difference between hot and inlet sides), these definitions are as bellow:

$$\Delta T_h = T_h - T_{\text{inlet}}$$

$$\Delta T_c = T_{\text{inlet}} - T_c$$

(1)

(2)
Beside the mentioned temperature differences, there is another scale for measuring the efficiency of a VT, named as the cold mass fraction. This factor (in fact the cold mass fraction manages the rate of cold flow as well as the cold temperature at the cold side) can be defined as bellow:

\[
\alpha = \frac{\text{Cold mass flow (m_c)}}{\text{Inlet mass flow (m_i)}}
\]  

(3)

Furthermore, we need a nondimensional scale for a correct analyzing regarding the VT’s performance, so, we present the isentropic efficiency as bellow:

\[
\eta_{\text{isentropic}} = \frac{\Delta T_{\text{inlet}} - T_c}{\Delta T_{\text{inlet}} - \Delta T_{\text{isentropic}}} = \frac{T_{\text{inlet}} - T_c}{T_{\text{inlet}}[1 - \frac{T_{\text{atm}}}{T}]} 
\]  

(4)

Here (in equation 4) we have these parameters; \( P_{\text{inlet}} \) or inlet pressure, \( \Delta T_c \) or cold temperature difference, \( \Delta T_{\text{isentropic}} \) or isentropic temperature difference and \( P_{\text{atm}} \) or the surrounding pressure.

4. Result and discussion

The DCVT is created based on this fact that there is another input line in addition to the main entrance of the vortex tube. The main entrance is located on the vortex chamber (as seen in Figure. 2) and the additional or extra input is fixed at the center of the control valve. So, it seems that the pressure at the additional line has some serious and strong effects on the thermal performance of the DCVT. This effect is not analyzed and reported yet.

**Figure 3:** Effect of nondimensional pressure \( P_n \) on cooling performance of DCVT

**Figure 4:** Effect of nondimensional pressure \( P_n \) on cooling performance of DCVT

**Figure 5:** Effect of nondimensional pressure \( P_n \) (fixed inlet pressure and variable extra injection pressure) on heating performance of DCVT with \( D=35 \text{ mm} \), \( d_o=10 \text{ mm} \), \( d_s=13 \text{ mm} \), \( L=600 \text{ mm} \), \( D_n=0.77 \), \( N=6 \) and \( P=10 \text{ bar} \) at \( Z/L=0.7 \)
For this purpose we will present a nondimensional pressure as the ratio of extra injection pressure to the main inlet pressure or $P_n=\frac{P_{ex}}{P}$. The main injection pressure is fixed on 10 bar and the extra injection pressure will be varied in the range of 1 to 4 bar, so, $P_n=0.1, 0.15, 0.2, 0.25, 0.3, 0.35$ and 0.4. The effect of this nondimensional pressure on cooling and heating effectiveness of the DCVT (with $D=35$ mm, $d_b=10$ mm, $d_a=13$ mm, $L=600$ mm, $D_n=0.77$, $N=6$ and $P=10$ bar) will be studied in this section. Figure 3 shows that there is an optimum value for the nondimensional pressure $P_n$ against the mass fraction axis. According to Figure 9, the cooling capability of the DCVT reaches a better situation and the DCVT works better than before when the nondimensional pressure is in the range of 0.1 to 0.2, and then, applying the greater values of $P_n$ destroys the separation phenomenon and the cooling efficiency allays extremely. When the nondimensional pressure $P_n$ increases from 0.1 to 0.2 the performance of the DCVT enhances 11.96% (4.5K). Because of an extra mass flow rate entering to the DCVT, it is expected that the structure of the optimum mass fraction on the cold mass fraction axis be changed, the trend of $\Delta T_c$ continues along the mass fraction axis just like a straight line with a negative slope (cold temperature difference decreases continually). Finally when the nondimensional pressure $P_n$ increases from 0.2 to 0.4 the cooling performance decreases 24.07%. According to the results of section 5.1 (Comparison between DCVT and RHVT with the same geometrical factors), a DCVT has lower heating efficiency compared to the cooling performance. It seems that this matter is because of the extra injection which is located at the center of the valve. This extra injection changes the energy pattern inside the main tube, especially near the valve (the location of hot exiting flow). So, this extra line and its features can have an extreme effect on the flow separation inside the DCVT. One of the most important thermophysical parameters of an inlet line is the pressure of the fluid. In this section we try to detect the extra injection pressure influence on the hot exit temperature (the hot exit place and the injection hole are in the same area at the end of the main tube).

As seen in Figure 4, the intensification in the nondimensional pressure (extra injection pressure) leads to an interesting improvement in heating capability of the DCVT. When the nondimensional injection pressure improves from 0.1 to 0.3 the heating performance of the DCVT elevates 37.23 % or 8.82K (the red arrow to top). The important thing is that this is the temperature of hot outlet and can be used directly for the heating purposes. But this is not the case for the performance improvement in the mentioned range, the pressure increasing has an opposite effect on the heating performance, so that, the heating effectiveness decreases for the nondimensional pressure $P_n$ improvements in the range of 0.3 to 0.4 around 4.74 K or 14.49% (the red arrow to down). As a conclusion, a DCVT with low $P_n$ is not appropriate to be used as a heating device and it should be forced by a high pressured extra injection line or $P_n$ be greater than 0.2. At a same time we measured the temperature on the main injection line of different nondimensional pressure $P_n$ (As seen in Figure 5). It can be seen that the warm front will be weakened with increasing $P_n$, continuously, in other words, the increasing $P_n$ pushes the warm front toward the hot exit and a DCVT can be used as an appropriate heating device by choosing an optimum nondimensional pressure $P_{n=0.3}$.

5. Conclusion

In this research, the experiments focus on the thermal performance of a special and interesting type vortex tube as the double circuit vortex tube (DCVT) based on different nondimensional pressure ratios (extra injection pressure $P_{ex}$/inlet pressure $P$) against the cold mass fraction. It should be said that the mentioned parameter its effects on the DCVT performance are not analyzed in previous researches. The aim of these tests is determining the possible optimum values regarding the mentioned parameter for the best thermal performance. The cooling capability of the DCVT reaches a better situation and the DCVT works better than before when the nondimensional pressure is in the range of 0.1 to 0.2, and then, applying the greater values of $P_n$ destroys the separation phenomenon and the cooling efficiency allays extremely.

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