A Novel Design of a Counter-Flow Vortex Tube by Suitable Automation at Hot and Cold Ends

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Abstract:
Separating the cold and hot air by using the principles of the vortex tube can be applied to industrial applications such as cooling equipment in CNC machines, heating processes, cooling suits, refrigerators etc. The vortex tube is well-suited for these applications because it is simple with no moving parts, quiet, compact, and does not use refrigerants. This study is devoted to the development and testing of an automated vortex tube that can meet the demands of time variant applications such as spot cooling during welding. This is achieved with the help of a moving blockage cone at hot end and orifice area controller at cold end. The performance of a counter-flow vortex tube is validated by comparing the results obtained from the present work with the literature.

Keywords: *counter-flow vortex tube, temperature separation, automation, orifice area controller, blockage cone*

1. Introduction

The vortex tube is a device which separates a high pressure air fed tangentially at inlet into two streams (Fig. 1) at lower and higher temperatures than the inlet air at cold and hot end exits respectively. This is possible with the help of blockage cone at hot end and orifice at cold end. The difference in the total temperature produced due to the swirl flow is first observed by Ranque [1] during the study in a cyclone separator. Later, Hilsch [2] performed experimental and theoretical studies to increase the efficiency of the vortex tube. He also found that angular velocity gradients in radial direction lead to this temperature separation. Several researchers also put forth the statements on temperature separation from their studies. Many articles are reviewed by Eiamsa-ard [3] on the basis of statements or hypotheses on the temperature separation in the counter-flow vortex tube. The design operating conditions and the optimal configurations of the vortex tube are discussed by Yilmaz *et al.* [4]. Several applications of the vortex tube cited in literature [5] include the dehumidification of gas samples, cooling the electronic control cabinets, refrigeration, polymerase chain reaction thermocycler applications, liquefying the natural gas and air-conditioning in the under-water habitation systems.

Hitesh, Aniket and Ashok [6] reviewed the experimental and numerical (Computational Fluid Dynamics) work carried out by various researchers. Also, review of various optimization studies using techniques such as Artificial Neural Network (ANN), Taguchi method is presented, which have not received due attention previously. The core objective is to give deliberate consideration to quality outcomes of fewer unattended research work on vortex tube.

Literature collection by Sudhakar and Mihir [7] lists the Ranque–Hilsch vortex tube experiments using air as the working fluid. The review focuses on the variables of interest and the important experimental results that have been obtained up to now. Another objective is to find curve-fitting equations using data from the literature which can provide a rough estimate of temperatures that are achieved, and which can be used in practice for preliminary vortex tube design. The effects of conical valve angle and length to diameter ratio on the performance of a counter flow Ranque–Hilsch vortex tube are predicted with artificial neural networks (ANNs) [8] by using experimental data. In the model, inlet pressure, conical valve angle, length to diameter ratio and cold mass fraction are used as input parameters while total temperature difference is chosen as the output parameter. The multilayer feed forward model and the Levenberg–Marquardt learning algorithm are used in the network and the hyperbolic tangent function is chosen as a transfer function. It is found that ANN can be successfully used to predict effects of geometrical parameters on the performance of the Ranque–Hilsch vortex tube with a good accuracy.

Other literature involves the theoretical and experimental studies based on flow and thermal characteristics and optimizing the geometrical parameters using genetic algorithm, artificial intelligence and fuzzy logic techniques. H. Pourier and W. Park [9] studied the variation of cold end orifice diameter by a valid numerical technique to understand the tem-

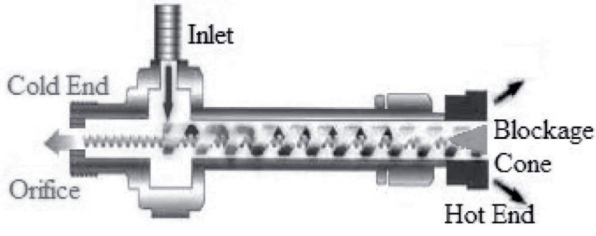

Fig. 1. Schematic of a Counter-flow vortex tube

perature separation. Earlier studies by B. Upendra *et al*. [10] and S. Nimbalkar and Michael Mueller [11] also suggest the requirement of optimum cold end orifice diameter in their experimental and computational studies. Genetic algorithm based optimization of the cold end orifice diameter is found using a back propagation neural network technique by H. Pourier *et al.* [12].

To meet the stringent usage of cold air, automation is required. Automation of counter-flow vortex tube finds important at this place in literature. The design requirements, development, validation and testing of an automated counter-flow vortex tube is further discussed here.

2. Methodology

The principle involved in the development and testing of automated vortex tube is shown (Fig. 2). A micro-controller controls the mass flow of streams using the blockage cone and orifice area controller at hot and cold ends respectively. Feedback to the micro-controller is measured using the temperature sensors at cold and hot end. After an initial calibration of the automated vortex tube, a computerized feedback program is created for maintaining the desired temperature at the cold end.

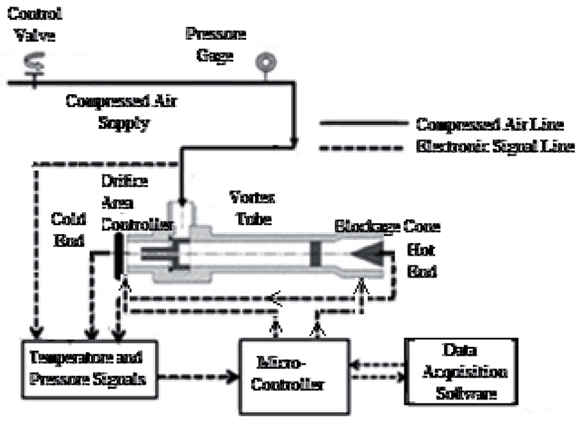

Fig. 2. Line diagram of experimentation in an automated counter-flow vortex tube

3. Design and Development

The design step plays a crucial step to predict the desired temperature after modeling followed by analyses of different parameters. The dimensions of the parts of counter-flow vortex tube are arrived after a series of preliminary experimental studies and consultation with the literature. Vortex tube diameter (inside) is fixed at 19 mm while the length is maintained at 190 mm. The blockage cone angle is decided at 30° to maintain the sensitivity in flow and temperature adjustments. The clearance between the different parts of the vortex tube is maintained within ±0.5 mm.

An iris diaphragm is used at cold end to have a variable diameter circular opening at cold end. This regulates the flow rate and thereby the desired temperature (temperature drop by 10°C as compared to inlet) can be maintained. The maximum and minimum apertures are maintained at 12 mm and 5 mm, respectively. The orifice area controller contains blades placed in a socket and assembled with a help of a pin. The overall assembly of the iris mechanism is shown in the Fig. 3. The aperture opening is controlled by changing the angle of the knob.

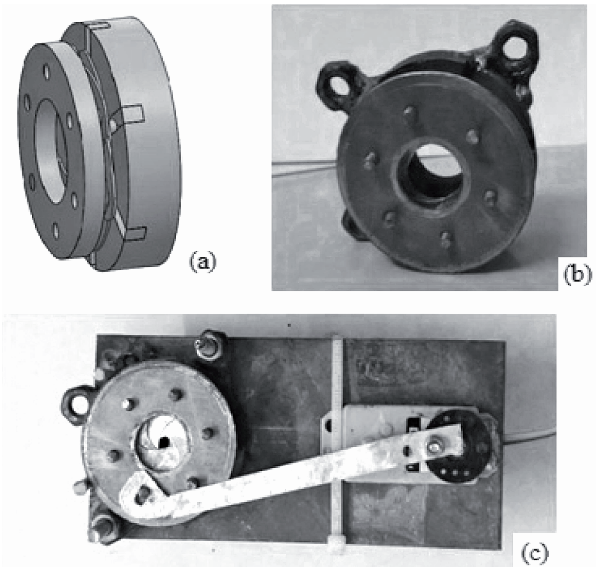

Fig. 3. Orifice Area Controller (a) Modeling, (b) Fabrication and (c) Assembly

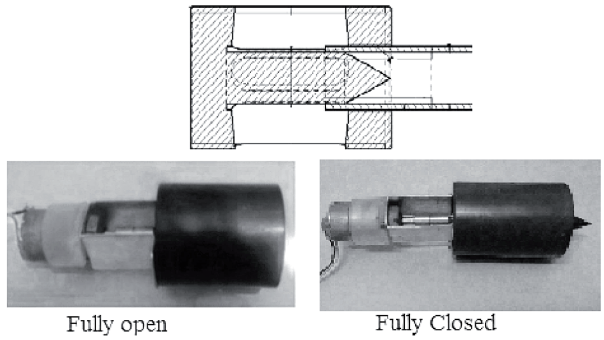

Fig. 4. Blockage Cone – Computer Aided Drawing and Operation

At the hot end, the blockage cone is placed at the centre of the annular flow exiting assembly as shown (cross-section) in Fig. 4. The cone is translated in (fully closed position) and out (fully open position) at the hot end of vortex tube, thereby facilitating the blockage at hot end. A threading arrangement is provided at the back side of the cone where rotational motion from a DC motor is converted into a linear motion.

4. Experimental Facility

The experimental arrangement primarily consists of a compressed (2 bar, absolute) and dry air from a compressor (Fig. 5) and transducers for the measurement of temperature and pressure at inlet and outlets by which the mass-flow rate is calculated. K-type thermocouple and LM35 sensors are used for temperature measurement. Piezo-resistive (strain) type of transducer is suited for the measurement of

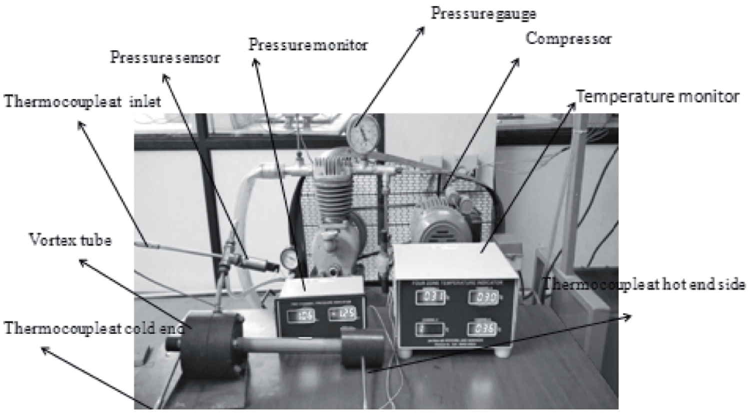

Fig. 5. Laboratory facility for the manual operation mode

pressure. Arduino Uno micro-controller interfaces with the personal computer for data acquisition and storage. The DC motor and servo motor receives signal from the micro-controller for controlling the blockage cone position at hot end and orifice diameter at cold end. The output voltages from the sensor are in the range 0-1 volts, acceptable to the micro-controller. A mapping function is employed for the conversion of units after calibration tests. Data acquisition and processing are facilitated with the help of cool mate and Microsoft Excel software packages, respectively. The fully automatic mode of operation of counter-flow vortex tube is shown in Fig. 6.

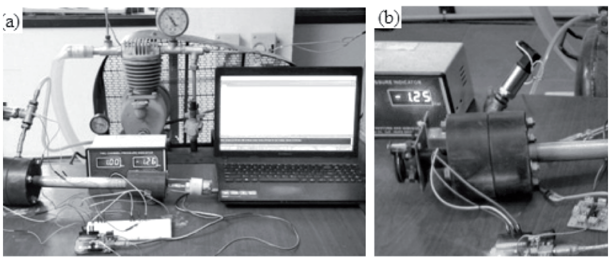

Fig. 6. Automation by feedback mode at (a) hot end and (b) cold end

5. Results and Discussion

Several experiments are carried out as the percentage of flow exiting the cold end varies depending on the blockage cone position at hot end and the diameter of orifice at the cold end. Cold gas fraction (μ) denotes the ratio of mass flow of air at cold end to the inlet of vortex tube. The actuators at hot and cold ends are employed as shown in Fig. 6 for the automated case, where the blockage cone position and orifice diameter are varied appropriately and the resulting temperature difference is found.

Total temperature differences between inlet and cold end, inlet and hot end are reported in Fig. 7 and Fig. 8, respectively. Due to the lower mass flow of air at cold end ($\mu < 0.5$), inner core air transfers the energy to peripheral air stream in a better way as compared to higher mass flow of air at cold end ($\mu > 0.5$).

The optimum ratio of cold end orifice diameter to vortex tube diameter is found by varying the orifice diameter ([9],[10] and [11]) in a given range. The results from these studies indicate the ratio to be maintained as 0.5. Lower than the optimum ratio leads to secondary circulation as reported by B. Upendra *et al.* [10]. This degrades the temperature separation effect due to streamwise circulation along the longitudinal direction of the vortex tube. Higher than the optimum ratio increases the short-circuiting of flow from inlet directly to the cold end exit without traversing towards the hot end. The present study employs a range of cold end orifice diameter from 5 mm to 12 mm for a vortex tube diameter of 19 mm leading to the range in ratio from 0.26 to 0.63. The optimum cold end orifice diameter is found as 9 mm from the present study and the ratio is calculated. This is found to be 0.47 and closely approximates with the P. Hassan [9].

This leads to a higher temperature separation between inlet and cold end (ΔT_c). Converse to this situation, the temperature separation between inlet and hot end (ΔT_h) is better when $\mu > 0.5$. Due to the higher mass flow of air at hot end ($\mu < 0.5$), inner core air transfers the energy to peripheral air stream in a better way as compared to lower mass flow of air at hot end ($\mu > 0.5$). However, the peak values for

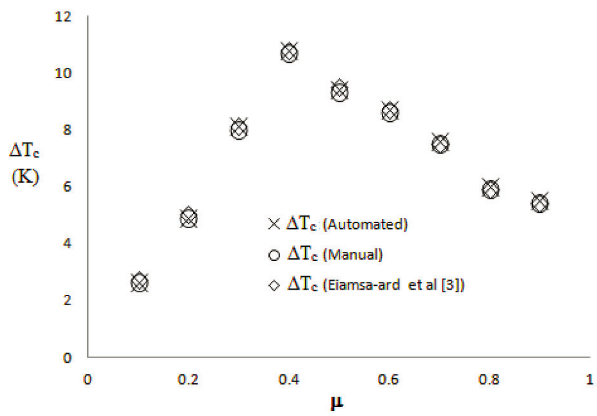

Fig.7. Temperature separation at the cold end

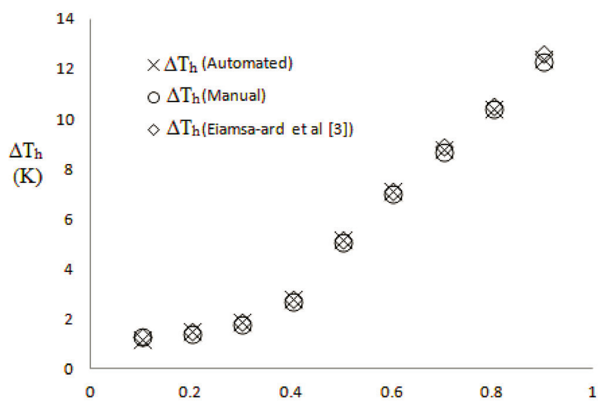

Fig. 8. Temperature separation at hot end

temperature separation is observed at μ = 0.4 for higher ΔT_c and μ = 0.9 for higher ΔT_h. The results from manual and feedback cases are found to be contiguous and consistent with the literature also. The trend as theoretically predicted is also matched with the literature. Hence the compressed air pressure can be increased further to increase ΔT_c. This can effectively replace a liquid coolant in a CNC machining operation. To accommodate the lubricity requirement, an additional sprayer can be installed along with the vortex tube facility. This design promotes the mutual benefit between an industry and the environment.

6. Conclusion

The present study deals with the performance of the vortex tube at lower inlet pressure of 2 bar (abs). The requirement of parts for the conversion from manual to automatic operation of the vortex tube is considered. To accomplish the need for automation, the flow controllers at hot and cold ends are designed and developed. The annular area at hot end is controlled using a blockage cone, whereas the cross-sectional area at cold end is regulated by a orifice area controller built using Iris mechanism. The behavior of the results obtained from the developed system are found to be in conformity with the literature. The system thus developed is considered to fulfil the benefits as a coolant facility in a CNC machine and also meet the requirements for spot cooling applications.

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