Review of vortex tube expansion in vapour compression refrigeration system

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Abstract. A vortex tube expansion device replacing the throttle valve is proposed to improve the efficiency of vapour compression refrigeration cycle by reducing the loss of irreversibility in expansion process. The vortex tube is well-suited for these applications because it is simple, compact, light, quiet. Thus, this paper presents an overview of the thermodynamic analysis of vapour compression refrigeration cycle with vortex tube expansion device using different refrigerants. The paper also reviews the experiments and the calculations presented in previous studies on temperature separation in the vortex tube. The temperature separation mechanism and the flow-field inside the vortex tubes is explored by measuring the pressure, velocity, and temperature fields.

1. Introduction
Use of vortex tube as an expansion device in vapor compressor refrigeration cycles is one of the promising cycle modifications to improve the system performance [1-2]. The vortex tube was basically developed for the gas expansion, working on the Ranque–Hilsch effect and lot of experimental and numerical works on that have been reported [3]. Hooper and Ambrose [4] first experimentally attempted to increase the refrigerating effect of a vapour refrigerator using a special version of Ranque–Hilsch vortex tube replacing the throttle valve. Other scientists have started to examine the principle behind the vortex tube expansion device in refrigeration systems in 1990s and proposed various refrigeration cycle configurations using vortex tube as expansion device. The COP improvements by using vortex tube were reported for the refrigerants R22, R134a, propane, ammonia, and carbon dioxide [5].

This paper reviews these research and explores the feasibility of using vortex tube in vapor compressor refrigeration cycles.

2. Thermodynamic analysis
Li et al. performed a thermodynamic analysis of different expansion devices for the transcritical CO₂ cycle [6]. A vortex tube expansion device and an expansion work output device were proposed to recover the expansion losses. The maximum increase in COP using a vortex tube or expansion work output device, assuming ideal expansion process, was about 37% compared to the one using an isenthalpic expansion process at evaporation temperature of 5°C and gas cooler exit temperature of 40°C. The increase in COP reduced to about 20% when the efficiency for the expansion work output device was 0.5. In order to achieve the same improvement in COP using a vortex tube expansion device, the efficiency of the vortex tube (ratio of enthalpy drop of cold mass to the isentropic enthalpy drop of total mass) had to be above 0.38.
Jahar Sarkar [7] analysed the optimization of compressor discharge pressure based on the maximum cooling COP for the vortex tube expansion transcritical CO$_2$ refrigeration cycle with two different cycle layouts: one is based on the Maurer model and another is based on the Keller model, which were shown in Fig.1 and Fig.2, respectively.

![Figure 1. Cycle layout of vortex tube expansion cycle for Maurer model](image1)

![Figure 2. Cycle layout of vortex tube expansion cycle for Keller model](image2)

For the analysis of vortex tube, a simple thermodynamic model has been used. The results showed that the use of vortex tube for Maurer model is more effective for higher temperature lift in terms of higher COP improvement and lower optimum discharge pressure over the basic cycle. For Keller model, effect of gas cooler exit temperature is similar to Maurer model, however, the improvement trend is
opposite for the evaporator temperature. Maurer model can give moderately more COP improvement than Keller model and lower cost due less system components. The expansion loss also decreases significantly by use of vortex tube. Expressions for optimum discharge pressure for both cycle models have been developed and these correlations offer useful guidelines for optimum system design and selecting appropriate operating conditions. Finally the improvement of cooling COP of transcritical CO$_2$ cycle by using vortex tube instead of expansion valve and also the effect on optimum discharge pressure have been presented for both the cycle layouts.

3. Experimental work
Currently, most of research about working gas is compressed air, only several literatures regarding the influence of HFCs on energy separation in vortex tubes are reported. Han X.et al. tested a vortex tube performance using R728, R744 (i.e. CO$_2$), R32, R22, R161 and R134a as working fluids [8]. The inlet pressure of the vortex tube was changed from 0.2 MPa to 1.3 MPa (abs), and the inlet temperature was adjusted to about 12°C. It was found that the temperature separation and outlet pressure increased with the rise of inlet pressure for R728 and R744, but there was an extreme value for R744 when the inlet pressure reached about 1.1 MPa (i.e. when the temperature reached a peak point of about 15°C), and the properties of the working fluids play significant roles in the temperature separation of the vortex tube. These properties include specific heat ratio, kinetic viscosity and thermal conductivity. Also, the throttling effects of working fluids themselves have influences on the temperature drop caused by vortex tube. In addition, the wall temperatures of the vortex tube hot end were measured; the phenomena of the cold end of the vortex tube were observed; and the conditions for the liquefying phenomena using HFCs were evaluated.

4. Qualitative, analytical and numerical work
Most of the past work efforts based on theoretical and analytical studies have been unsuccessful to explain the energy separation phenomenon in the tube. Also, a few attempts of applying numerical analysis to the vortex tube (see Table 1) have failed to predict the flow and temperature fields due to the complexity of the flow and energy separation process inside the tube. The failure of those calculations of vortex tube flows was due to the choice of oversimplified models to describe the flow. In view of the recently computational work, the use of various turbulence models in predicting the temperature separation such as the first-order or the second-order turbulence models, leads to fairly good agreement between the predicted and the experimental results better than those found in the past decades, especially for using the second-order turbulence model.

| Investigator       | Flow considered | Model                      | Method         | Results compared with measurements |
|--------------------|-----------------|----------------------------|----------------|-----------------------------------|
| Linderstrom        | Incompressible  | Zero-equation              | Stream-funcion | Poor but just trend               |
| Gustol and Bakken  | 2D compressible | k- $\varepsilon$ model     | FLUENT™ code   | Fairly good                       |
| Promvonge [13]     | 2D compressible | ASM and k- $\varepsilon$ model | Finite volume | Good                              |
| Behera et al. [14] | 3D compressible | k- $\varepsilon$ and RNG k- $\varepsilon$ model | Star-CD code | Fairly good                       |
| Eiamsaard and Promvonge [15] | 2D compressible | ASM and k- $\varepsilon$ model | Finite volume | Good                              |
5. Conclusions
The vortex tube has no moving parts and does not break or wear and therefore requires little maintenance. The vortex tube expansion transcritical CO\textsubscript{2} cycle for the Maurer model can give higher COP improvement for lower cooling temperature applications. The maximum increase in COP using a vortex tube or expansion work output device, i.e., assuming ideal expansion processes, is about 37\% compared to the one using an isenthalpic expansion process. In view of the recently computational work, the use of the second-order turbulence model in predicting the temperature separation leads to good agreement between the predicted and the experimental results.

Using vortex tube in vapour compressor refrigeration cycles is feasible, and further research is needed on temperature and energy separation mechanism in vortex tube.

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References
[1] La D, Dai YJ, Li Y, Wang RZ, Ge TS. 2010. Technical development of rotary desiccant dehumidification and air conditioning: A review. Renewable and Sustainable Energy Reviews. 14, 130-147.
[2] Jia CX, Dai YJ, Wu JY, Wang RZ. 2006. Analysis on a hybrid desiccant air-conditioning system. Applied Thermal Engineering. 26, 2393-2400.
[3] Li Y, Sumathy K, Dai YJ, Zhong JH, Wang RZ. 2006. Experimental study on a hybrid desiccant dehumidification and air conditioning system. Journal of Solar Energy Engineering. 128, 77–82.
[4] F.C. Hooper, C.W. Ambrose. 1973. Improved expansion process for the vapor refrigeration cycle, SAE preprints. 811–812.
[5] Zhang LZ. 2006. Energy performance of independent air dehumidification systems with energy recovery measures. Energy. 31, 1228-1242.
[6] Bourdoukan P., Wurtz E., Joubert P. 2010. Comparison between the conventional and recirculation modes in desiccant cooling cycles and deriving critical efficiencies components. Energy. 35, 1057-1067.
[7] Panaras G, Mathioulakis E, Belessiotis V. 2011. Solid desiccant air conditioning systems design parameters. Energy. 36, 2399-2406.
[8] Liu W, Lian Z, Rademacher R, Yao Y. 2007. Energy consumption analysis on a dedicated outdoor system with rotary desiccant wheel. Energy. 32, 1749-1760.
[9] Sheng Y., Zhang Y., Zhang G. 2015. Simulation and energy saving analysis of high temperature heat pump coupling to desiccant wheel air conditioning system. Energy. 83, 583-596.
[10] Antonellis S. D, Joppolo C. M., MolinaroliL. Pasini A. 2012. Simulation and energy efficiency analysis of desiccant wheel systems for drying processes. Energy. 37, 336-345.
[11] Linderstrom-Lang CU. Gas separation in the Ranque–Hilsch vortex tube. 1964. International Journal of Heat and Mass Transfer.7, 1195–206.
[12] Gutsol AF, Bakken JA. 1998. A new vortex method of plasma insulation and explanation of the Ranque effect. Journal of Physics D: Applied Physics.31, 704-711.
[13] Promvonge P, Eiamsaard S. 2005. Investigation on the vortex thermal separation in a vortex tube refrigerator. Science Asia Journal. 31(3), 215–230.
[14] Behera U, Paul PJ, Kasthurirengan S, Karunanithi R, Ram SN, Dinesh K, et al. 2005. CFD analysis and experimental investigations towards optimizing the parameters of Ranque–Hilsch vortex tube. International Journal of Heat and Mass Transfer. 48(10), 1961-1973.
[15] Eiamsa-ard S, Promvonge P. 2006. Numerical prediction of vortex flow and thermal separation in a subsonic vortex tube. Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering). 7(8), 1406 – 1415.