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Analysis of the unsteady heat and mass transfer processes in a Ranque–Hilsch vortex tube: Tube optimization criteria

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A B S T R A C T

Although numerous experiments and numerical calculations have been carried out in order to study, with different parameters, the relationship between the flow structure and energy separation performance in a vortex tube, there has been less progress on its design optimization, which is due to the lack of a systematic analysis of the flow structure inside the vortex tube. According to the evidence, the large-scale vortex structures resulting from the vortex breakdown and vortex core precession determine the heat and mass transfer processes and flow structure in the vortex tube, and they are sensitive to the operation conditions. To study the vortex structure, attention can be paid to the shape of the reverse flow boundary and the location of the stagnation point, because they are the bond between the hot and cold streams. Based on the understanding of the energy separation mechanism and different flow structures inside a vortex tube, this study proposed a flow structure inside the main tube that bears the best energy separation performance as the optimization criteria for the main tube design. Based on a basic description of the counter flow structure in a confined slender tube, a preliminary quantitative tube design procedure can be realized to achieve the key parameters of the main tube, such as length, diameter, and diameter of the cold exit.

1. Introduction

Since it was discovered in 1933 by Ranque, a French engineer, the unique energy separation phenomenon of the Ranque-Hilsch vortex tube (RHVT) has always been a mystery concealed by the intense turbulence [1]. Without any moving component, the compressed gas goes through the tangential inlet nozzles and generates a swirling flow in the main tube of the RHVT, as shown in Fig. 1. After the separation of the flow and energy inside the tube, a rise in gas temperature can be obtained at the hot exit away from the inlet, and at the same time, a drop in temperature is achieved at the cold exit near the inlet. The temperature difference between the two opposite exits can be as high as 100 °C, with inlet pressure of typically 0.6 MPa, and a control valve is located at the hot end to adjust the mass flow rate and energy separation performance at the exits. The energy separation phenomenon has attracted the interest of physicists owing to the heat and mass transfer process inside the large-scale vortex structure, which can be related to the mechanism of Maxwell's demon [2] and the accretion disk [3]. Besides, it is also utilized by engineers for various industrial applications as an energy and mass separator device [4], and especially for the latest applications proposed in various thermodynamic systems [5–7] and in the gas industry [8–10].

The energy separation is breed within the gas flow field; thus, achieving an unambiguous flow structure inside the RHVT is the key to understand the energy separation process. However, both the observation and analysis of the flow structure and energy separation are trapped in the complicated swirling flow, especially on the quantitative level. For a detailed review on energy separation, refer to [11–13]. Although no conclusion has been reached in past studies on the specific mechanisms that cause energy separation, a basic flow structure and energy transfer pattern were identified recently, as shown in Fig. 1 [14,15]. According to the experimental observations and numerical calculations [16–18], the gas flow does not go straight to the cold exit, even if it is very close to the inlet. After generating a swirl flow inside the tube, during the process heading to the hot end, part of gas flow breaks away from the main stream and forms a reverse flow near the axis owing to vortex breakdown. Then, an iso-surface on which the axial velocity is zero can be drawn to separate the cold flow at the core and the hot flow at the periphery with a stagnation point located at the axis under a time-average state. Such a virtual reverse flow boundary can be regarded as the bridge through which the heat and mass transfer processes take place between the inner and outer layers, and the

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Nomenclature

T	temperature (K)
p	pressure (Pa)
m	mass flow rate (kg s^{-1})
Z	axial distance (m)
L	length of main tube inlet (m)
D	diameter (m)
Re	Reynolds number
Ma	Mach number
v	velocity (m s^{-1})
r	radial distance (m)/dimensionless of radius
R	radius (m)
Ψ, ψ	Stokes stream function
U	dimensionless axial velocity
$\bar{R}$	the specific gas constant
Q	dimensionless flow rate
F	dimensionless swirl velocity

Greek symbols

ε	cold mass fraction
γ	the adiabatic exponent
λ	decay rate in the axial direction

Subscripts

c	cold gas
h	hot gas
ϕ	tangential direction
z	axial direction
r	radial direction
in	inlet gas
p	pipe component
s	swirl component
ft	flow-through component
0	state at null point/stagnation point

Abbreviations

RHVT	Ranque–Hilsch vortex tube
CRZ	central recirculation zone
PVC	precessing vortex core
PDPA	phase Doppler particle analyzer
PIV	particle image velocimetry
CR	annular circulation region

gas flow distribution can be divided by the stagnation point into a heat transfer zone and a swirl decay zone. From this point of view, the energy separation is mainly completed in the heat transfer zone, and the swirling flow decays owing to the wall friction during its proceeding to the hot end. However, with these observed flow structure and qualitative explanations on energy separation, the design of a high efficiency vortex tube is still far away.

Various factors, such as inlet pressure, cold mass fraction, working fluid properties, and geometrical parameters, can affect the energy separation performance (defined by the temperature difference between the hot and cold exit, $\Delta T = T_h - T_c$), and extensive studies have been published to achieve the optimal design of an RHVT. Yilmaz et al. [19] reviewed the experimental investigations conducted before 2007 on energy separation performance, with variables including geometrical parameters, mass flows, gas properties, reservoir conditions, and internal flow parameters, and they suggested the best ranges of these parameters after comparisons among the past results. Subudhi and Sen [20] extracted overall and particular correlations and curve-fitting equations between the various parameters and the energy separation performance based on the past experiments using air as the working fluid; however, the relative errors in all the curve-fitting equations ranged from 24% to 350%. Devade and Pise [21], from the past experimental and numerical studies, concluded and counted the different effects of almost 14 parameters on the energy separation performance, and they suggested that attention should be paid to the location of the stagnation point, which has a significant effect on the performance. Besides, the proposed optimization investigations, such as the artificial neural network and Taguchi method, were reviewed by Thakare et al. [13]. These are statistical approaches based on the existing experimental data and cannot offer information about what happens on the fluid field and energy separation process in an RHVT. Liew [15] built a quantitative energy separation model with the analysis of the heat transfer processes, in which the outlet temperature could be calculated with the measurement of the nozzle outlet Mach number, and the

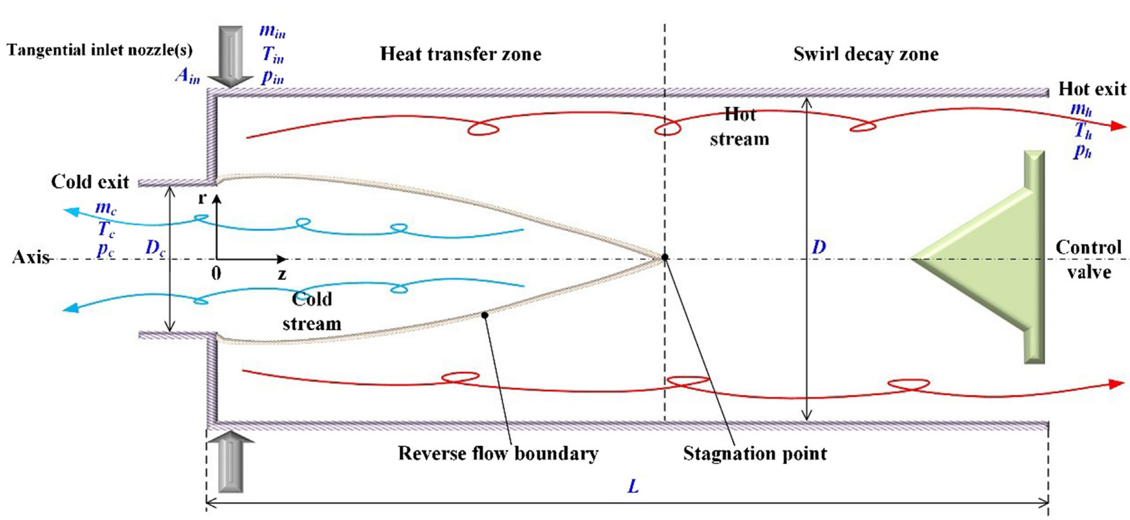

Fig. 1. Basic flow structure in RHVT.