Cryogenics 63 (2014) 94–101

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Performance optimization of a miniature Joule–Thomson cryocooler using numerical model

P.M. Ardhapurkar [a,b], M.D. Atrey [a,*]

[a] Mechanical Engineering Department, IIT Bombay, Mumbai 400 076, India
[b] S.S.G.M. College of Engineering, Shegaon 444 203, India

ARTICLE INFO

Article history:
Received 14 April 2014
Received in revised form 9 July 2014
Accepted 15 July 2014
Available online 27 July 2014

Keywords:
Joule–Thomson cryocooler
Heat exchanger
Optimization
Cooling capacity
Performance

ABSTRACT

The performance of a miniature Joule–Thomson cryocooler depends on the effectiveness of the heat exchanger. The heat exchanger used in such cryocooler is Hampson-type recuperative heat exchanger. The design of the efficient heat exchanger is crucial for the optimum performance of the cryocooler.

In the present work, the heat exchanger is numerically simulated for the steady state conditions and the results are validated against the experimental data available from the literature. The area correction factor is identified for the calculation of effective heat transfer area which takes into account the effect of helical geometry. In order to get an optimum performance of the cryocoolers, operating parameters like mass flow rate, pressure and design parameters like heat exchanger length, helical diameter of coil, fin dimensions, fin density have to be identified. The present work systematically addresses this aspect of design for miniature J–T cryocooler.

1. Introduction

Joule–Thomson (J–T) cryocoolers have been widely used for many applications such as cooling of infrared detectors, cryosurgery probes, thermal cameras, and missile guidance systems, due to their special features such as simple configuration, compact structure and rapid cooldown characteristics. It consists of a recuperative heat exchanger, an expansion device, and an evaporator. Fig. 1 shows the schematic of a J–T cryocooler. The thermodynamic performance of these cryocoolers is mainly governed by the effectiveness of the heat exchanger. Usually, the heat exchanger is Hampson-type finned tube heat exchanger. The finned tubes are helically wound on mandrel and shield is provided on the outside of the coil. The working fluid such as nitrogen, argon at high pressure flows inside the helically coiled finned tube, and returns over the fins after expansion through an orifice at the end of heat exchanger. The low-pressure stream circulates over the finned tube surface in opposite direction to the high-pressure stream. The process 1–2 represents the heat rejection by the hot fluid at high pressure, whereas the process 4–5 is the heat gain by the cold fluid at low pressure.

Several researchers have worked to compute steady state performance of the J–T cryocooler [1–4]. Few studies on transient analysis of J–T cryocooler have also been reported in the literature [5–7]. The design of Hampson-type heat exchanger is crucial due to its complex geometry, variation in thermo-physical properties of fluid and thermal losses. Ng et al. [1] and Xue et al. [2] reported experimental and numerical study of the J–T cryocooler for steady-state characteristics with argon as a working fluid. Chua et al. [4] have argued that, Ng et al. [1] and Xue et al. [2], in their numerical work, have not used the actual heat transfer area for the low pressure return stream in the helical heat exchanger, but have used some correction factors to compute effective area of heat transfer in the return line. Additionally, there is very little information available in the literature related to the effect of various operating and design parameters on the performance of the J–T cryocooler.

The design of recuperative heat exchanger for its optimum performance depends on many parameters such as type of fluid, mass flow rate, supply pressure, and various design parameters such as heat exchanger length, fin tube diameter, helical diameter of coil, fin dimensions, and fin density. In the present work, numerical simulation of the heat exchanger is performed to carry out the parametric study for the optimum performance of the cryocooler.

2. Numerical model of heat exchanger

2.1. Heat exchanger geometry

2.1.1. Calculation of flow area for low pressure stream in shell side

In the present study, the specifications of the heat exchanger are taken from the literature [1], which are given in Table 1. The

* Corresponding author. Tel.: +91 22 2576 7522; fax: +91 22 2572 6875.
E-mail addresses: pm_ardhapurkar@yahoo.com (P.M. Ardhapurkar), matrey@iitb.ac.in (M.D. Atrey).

http://dx.doi.org/10.1016/j.cryogenics.2014.07.006
0011-2275/

Nomenclature

A	area, m^2
A_s	surface area, m^2
Cp	specific heat capacity, J/kg K
d	diameter, m
d_f	fin tube diameter, m
D_h	hydraulic diameter, m
D_{hel}	mean diameter of helical coil, m
f	friction factor
G	mass flux, kg/m^2 s
h	heat transfer coefficient, w/m^2 K
k	thermal conductivity, w/m K
L	length of heat exchanger, m
$\dot{m}$	mass flow rate, kg/s
n	fin density, number of fins per meter
$N_{fins/coil}$	number of fins per coil turn
P	pressure, Pa
p	perimeter of heat transfer, m
Pr	Prandtl number
Re	Reynolds number
t	mean fin thickness, m
T	temperature, K
u	mean velocity, m/s

Greek symbol

ΔP	pressure drop, Pa
ρ	density, kg/m^3

Subscripts

a	ambient
c	cold fluid
ci	capillary inside
co	capillary outside
h	hot fluid
i	inside
in	inlet
m	mandrel
mi	mandrel inside
mo	mandrel outside
o	outside
out	outlet
r	radiation
s	shield
si	shield inside
so	shield outside
w	wall

accurate calculation of the flow area for the low-pressure stream is essential for modeling the finned tube heat exchanger. Fig. 2 shows the cross-section of the finned tube heat exchanger. In order to calculate flow area for low pressure stream, A_c, cross-sectional area of tube without fins and area of fins in one coil turn is subtracted from the total annular area between shield and mandrel. It is expressed in Eq. (1)

$$A_c = \frac{\pi}{4}(d_{si}^2 - d_{mo}^2) - \frac{\pi}{4}[(D_{hel} + d_{co})^2 - (D_{hel} - d_{co})^2] - t(d_f - d_{co}) \times N_{fins\ per\ coil} \quad (1)$$

where d_{si} is inside diameter of shield, d_{mo} is outside diameter of mandrel, D_{hel} is diameter of the helical coil, d_f is finned tube diameter, d_{co} is the fin root diameter, and t is mean thickness of the fin. $N_{fins\ per\ coil}$ represents the number of fins per turn of the coil, which is given in Eq. (2).

$$N_{fins\ per\ coil} = \frac{\pi D_{hel}}{\text{fin pitch}} \quad (2)$$

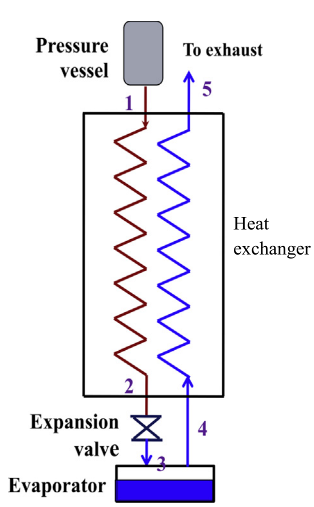

Fig. 1. J–T cryocooler.

Alternatively, the projected area method [8] can be used to calculate flow area and outside perimeter of the finned tube. According to this method, the total available free flow area on shell side, A_c, neglecting diametrical clearance is given in Eq. (3).

$$A_c = \pi D_{hel}[(d_f - d_{co})(1 - n \times t)] \quad (3)$$

where n is number of fins per m.

2.1.2. Calculations of surface area & Perimeter of finned tube

In order to calculate outside perimeter of the finned tube, calculations are done for one turn of the coil neglecting the surface area of tips of the fins. The outside surface area of finned tube is calculated by subtracting surface area occupied by base of all fins on tube in one coil turn from the surface area of bare capillary tube and the surface area of two sides of all fins in one coil turn. Therefore, surface area offered by the outer finned surface in one coil turn, A_s, is calculated as given in Eq. (4).

$$A_s = \pi^2\left[\frac{n}{2}(d_f^2 - d_{co}^2) + d_{co}(1 - nt)\right]D_{hel} \quad (4)$$

Hence, perimeter of outer finned surface (surface area per unit axial length), p_{co}, is obtained as

Table 1
Specifications of the heat exchanger [1].

Parameters	Dimension
Inside diameter tube, d_{ci} (mm)	0.3
Outside diameter tube, d_{co} (mm)	0.5
Inside diameter of mandrel, d_{mi} (mm)	2.3
Outside diameter of mandrel, d_{mo} (mm)	2.5
Inside diameter of shield, d_{si} (mm)	4.5
Outside diameter of shield, d_{so} (mm)	4.8
Length of heat exchanger, L (mm)	50
Straight length of tube (mm)	549.5
Diameter of helical coil, D_{hel} (mm)	3.5
Pitch of tube (mm)	1.0
Number of turn of tube	50
Height of fin (mm)	0.25
Pitch of fin (mm)	0.3
Thickness of fin, t (mm)	0.1
Fin density (fins/mm)	3.3