Development of a Sintered Porous Neck Filter for miniature Joule Thomson Cryo-cooler for cooling Infrared detectors

Mayank Singhal¹, Rajesh Kumar², R.S. Walia³ and S.K. Pandey¹
¹Defence Research and Development Organisation, Delhi, India
²Delhi Technological University, Delhi, India
³Punjab Engineering College, Chandigarh, India

E-mail: mayanksinghal25@gmail.com

Abstract. One of the primary requirements for operation of Infrared (IR) detector systems for defence applications is the availability of a reliable miniature cryocooler. Due to a simple configuration, compact and light structure and rapid cool down characteristics, miniature Joule Thomson (JT) cryocoolers are considered ideal for IR detector systems. The need for high purity gas supply is a main concern in order to ensure long and reliable operation of Joule Thomson miniature cryocoolers. Minute solid particles are the common and problematic impurity which on being lodged in the cooler orifice hampers the cryo-cooling process of the cooler by choking which affects the operation of IR detector packaged in an Infrared detector cryochamber or dewar.

The paper focuses on realization of sintered porous neck filter, the developmental aspects of the same and its characterization. In the present work a sintered porous neck filter with 5µm pore size and a filter porosity of nearly 35% was developed. The filter developed was assembled at the warm end of the cooler and the cooler assembly was integrated in the IR cryochamber for in system evaluation and confirmation of the desired quality of the developed porous filter.

Keywords: JT cooler, sintered neck filter, porosity, pore size

1. Introduction

IR detectors in military use find application in the field of missile guidance, tracking of projectile systems and ground surveillance [1]. Though uncooled night vision technologies are available, most of IR detectors used for military applications are cooled. In terms of working ranges, resolution and ability to recognize/track fast moving objects in dynamic infrared scenes cooled systems are still considered to be superior [2, 3].

A cooling medium must be provided, and the detector must be mounted inside a vacuum encapsulation, called IR detector cryochamber or Dewar, so that it will remain cold and still be accessible to the infrared. There are number of long life coolers available for space applications covering a wide variety of thermodynamic cycles and configuration types [4]. However in case of IR detectors thermoelectric, Stirling and JT coolers are mainly used [5].

Miniature Joule-Thomson (JT) coolers are widely used for rapid cooling of infrared detectors, cryosurgery probes, thermal cameras, and missile homing guidance systems, due to their special features of simple configuration, compact structure and rapid cool down characteristics. It is the isenthalpic expansion of gas, known as the Joule Thomson effect [6] which forms the basis of the miniature JT cooler which is the one used for cryo-cooling to achieve temperatures of ~ 77 K suitable for IR detector operation in the present study.

These JT coolers may be operated with or without filter assemblies, however the latter may be preferred on account of expected better qualitative performance by eliminating various contaminants helpful in preventing choking. However, a clear quantitative
assessment of the performance of an IR detector cooling performance by introducing a filter assembly has not yet been investigated. Hence, it is worthwhile to investigate the same and this forms the prime motivation for the present work.

2. Configuration of JT cooler

The miniature finned tube JT cooler along with its main parts including the filter assembly is shown in Fig. 1. In case when the filter is used, high pressure nitrogen gas of high purity is passed through a conical sintered porous filter, situated at the main inlet port or the neck of the JT cooler, as shown in Fig. 1(b). The importance of using a sintered porous filter of about 5µm porosity is to arrest all contaminants larger than 5µm in the incoming gas in order to avoid any choking, which normally occurs in the expansion nozzle of the JT cooler, resulting in either restricting or fully blocking the gas flow.

A conical, porous sintered filter, as shown in Fig. 1(c), is thus integrated at the inlet of the cooler assembly so that the contaminant present in the gas supply can be arrested at the beginning itself, i.e., at the main entry of the cooler. The gas after passing through the filter is cooled by the outgoing cold gases (expanded earlier), flowing between outside of the finned tube and inside of the inner Dewar tube, at constant pressure. Thus, the finned tube acts as a recuperative heat exchanger, with counter flow of incoming and outgoing gases. This heat exchanger is basically a fine tube of a bore of about 0.3mm, usually made of copper-nickel alloy with copper fins soldered to its outside surface, with a specific fin density, and wound in the form of closely of coiled helix around the tube. Thereafter, the finned tube is wound over a cylindrical mandrel made of a low thermal conductivity material, such as, Micarta or Stainless Steel (SS), to give the JT cooler its final shape. The finned tube is then soldered to the inlet port and outlet port at the two ends of the cooler. A micro-orifice cap is then integrated on the outlet port, which acts as a nozzle, where the final expansion of the gas actually occurs at constant enthalpy, resulting in cooling due to the Joule-Thomson effect.

Fig. 1: a) JT Mini-cooler, b) its sectional view and c) Sintered Porous Neck Filter
3. Development of Sintered porous Bronze Filters

Technology of powder metallurgy (P/M) is used extensively nowadays as it is a highly economic method for producing porous parts. In powder metallurgy, costly machining processes are reduced or eliminated resulting in less scrap loss [7-9].

Desired properties of metals, which would normally not alloy easily, can be achieved by combining different metal powders or mixtures of metal and non metal powders. Copper based P/M materials are widely used in industry at par with other P/M materials such as those based on iron, steel and aluminium [10]. The porous sintered parts with a porosity ranging from 20% to 90% have found many applications such as self-lubricating bearings and filters in which the pores form an interconnected three dimensional network. P/M bronze parts are frequently used for structural applications, however, low hardness and strength along with poor wear resistance limits their usage [11]. Structural parameters such as porosity and pore size depend on processing parameters such as powder size range, compacting pressure, sintering temperature and time [12-16].

Filters constitute one of the major applications of porous materials. The most commonly used powders include bronze, stainless steel, nickel, nickel based alloys, titanium and aluminium. The ability to achieve close control of porosity and pore size is the main reason that metal powders are used in filter applications.

Spherical 89/11 bronze powders are amongst the most preferred materials used to make filters [17] as these powders are capable of having closely controlled particle size. Bronze filters usually are made by gravity sintering of these spherical powders [17,18]. The effective pore sizes of filters generally ranges from 5 to 125 µm [18].

Porosity of the filter developed is ensured so that the required cooling is achieved by JT cooler which indirectly helps in trouble free operation of IR detector used for imaging. The density, pore size, pore size distribution, and permeability determine the overall performance of a porous material in an application.

The most critical challenges in developing such filters include achieving the desired porosity and its extensive characterization along with achieving the required dimensional accuracy of the components. Thus, micro-structural characterizations as well as weight, dimension and % porosity measurements are equally important prior to them being employed in a cost intensive JT cooler assembly.

The specifications of the developed Sintered Porous Bronze Filter, to be employed as neck-filter for the JT cooler are based on the orifice size of the JT cooler, the availability of space at the inlet port and integration/compatibility constraints.

Fig. 2 below describes the process flow for the development of the sintered porous neck filter and the details of each process are discussed subsequently.

![Process flow for development of sintered porous neck filters](image-url)
3.1 Sieving:

Sieving of the as-received bronze powder is conducted using a sieve shaker. The size fraction of -325 +400 mesh (37 to 45μm) was selected for the required filters. This narrow size fraction was obtained after repeated sieving until there was complete absence of any -400 mesh size particles. This is essential as the presence of -400 mesh size powders essentially leads to undesirable densification of the powder.

3.2 Tooling and Powder filling

Tooling which is negative shape of final part is an element of high precision and high durability. A suitable stainless steel (SS) mould was designed and fabricated prior for processing of the porous filters. A dry graphite lubricant was applied to the internal surfaces of both the halves of the mould prior to powder filling in order to avoid direct contact between the bronze powder and the mould surface. The surface smoothness was also ensured after coating as any surface roughness will leave an impression on the final developed component. Gas atomized spherical bronze powders sieved to narrow size fractions are filled in the mould and vibrated for 15 to 20 min. Necessary care was taken during powder filling, tapping and while vibrating the moulds to ensure that powder mass remains constant before and after this stage.

3.3 Sintering

Sintering is a thermal cycle consisting of heating the compacted part at an elevated temperature which is below its melting point. During the process powder particles fuse together, voids between the particles decrease, and eventually a dense solid body is obtained. Typically, bronze powder is sintered at 800 to 1000°C for 20 min in a reducing atmosphere to form a liquid phase between the particles and cooling thereafter ensures that a strong metallurgical bond is formed at the contact points between the powder particles [18]. The moulds filled with powder are then loaded in the tubular hydrogen furnace for sintering. Several trial experiments were carried out in order to optimize the sintering temperature and soaking duration for obtaining ~ 35% density. In the present investigation these experiments were carried out using the -325+400 mesh bronze powder. The most appropriate sintering temperature and soaking duration were found to be 830°C and 30 min to achieve the desired density for the development of the filters. Necessary precautions were taken to extract the components from the mould subsequent to completion of the sintering process. Also, the components were cleaned thoroughly with compressed air to remove any possible remnants of the mould or any other impurities.

Since the filter specifications for necessary compatibility are quite stringent, it was essential to characterize the developed filters prior to testing it with the JT cooler assembly. Thus the characterization and assessment of the filters include viz., adherence to required dimensional accuracy, adherence to projected filter mass, filter porosity and material phase purity. Subsequently, the porous neck filter assembly was tested in conjunction with the JT cooler assembly and a comparative assessment in terms of the cold temperature and the cool down time with filter and without filter condition was carried out.
4. Results and Discussion

The specimen components were sintered and used for density, dimensions measurements and microstructure evaluation. The micro-structural characterization as well as weight, dimension and % porosity measurements were carried out on the neck filter. A porous SEM image of a sintered bronze filter is shown in Fig. 3. During our experimental work, it was calculated that the porosity of our specimen is comparable to one reported in literature [19].

![SEM image of porous sintered bronze filter](image)

Fig. 3: SEM image of porous sintered bronze filter

The measured dimensions of the bronze filters are given in Table 1. The density of this filter was measured by the Archimedes water displacement method after impregnating the filter with xylene. Table 2 presents the density and the corresponding porosity of the filter.

Table 1: Measured Dimensions of bronze filters samples

| Sample number | Wt. (g) | 1     | 2     | 3     | 4     |
|---------------|---------|-------|-------|-------|-------|
|               |         | 0.067 | 0.069 | 0.066 | 0.062 |
| d1 (mm)       |         | 3.93  | 3.92  | 3.94  | 3.91  |
| d2 (mm)       |         | 2.46  | 2.5   | 2.48  | 2.41  |
| d3 (mm)       |         | 1.84  | 1.8   | 1.82  | 1.85  |
| L (mm)        |         | 3.0   | 3.04  | 3.02  | 3.02  |
| T (mm)        |         | 0.6   | 0.6   | 0.6   | 0.6   |
Table 2: Density and porosity of bronze filters

| Sample number | 1     | 2     | 3     | 4     |
|---------------|-------|-------|-------|-------|
| $W_{ss}$, air (g) | 0.067 | 0.069 | 0.062 | 0.068 |
| $W_{ss+x}$, air (g) | 0.069 | 0.071 | 0.064 | 0.070 |
| $W_{ss+x}$, w(g) | 0.057 | 0.059 | 0.053 | 0.058 |
| Vol (cm$^3$) | 0.012 | 0.012 | 0.011 | 0.012 |
| $\rho$ (g/cm$^3$) | 5.58 | 5.75 | 5.64 | 5.67 |
| $\phi$ (% th) | 63.7 | 65.6 | 64.3 | 64.7 |
| Porosity | 36.3 | 34.4 | 35.7 | 35.3 |

An XRD spectrum of the sintered sample, Fig. 4 [pepdf -501333], shows the Copper-Zinc phase of the material with a pure cubic structure. The corresponding SEM images of the neck filter with pore sizes ranging between 10 to a 30 μm are shown in Fig. 5 along with photographs of the developed hardware.

Fig. 4: XRD analysis of sintered filter sample 2

Fig. 5: Photograph of developed neck filter (sample 2) with corresponding SEM image

Further, in order to critically evaluate the porous neck filter it is required to integrate it with the JT cooler assembly. This is quite arduous and should be done with utmost care.
The assembly of the porous neck filter in the JT cooler assembly is shown in Fig. 6(a), which also clearly depicts the relative size of the filter with respect to the JT cooler. JT cooler assembled in glass dewar is shown in Fig. 6(b). The latter assembly was used for checking the flow of nitrogen through the cooler.

Fig 6: (a) Assembly of Filter in JT cooler                 (b) JT Cooler assembled in a glass dewar

JT coolers integrated with developed sintered porous filters were finally tested in an infrared detector cryochamber or Dewar for cooling parameters such as Cool Down Time (CDT) and achieved cold temperature. All the four sample filters from the lot developed were assembled into different available JT coolers and were tested in a sealed IR detector cryochamber or Dewar for CDT which is basically the time required for the Infrared detector packaged in a cryochamber to reach a cryogenic temperature. A single Dewar or Infrared detector cryochamber was used to minimize uncertainties due to variation in quality of vacuum in different Dewars or due to integration of Dewars in general. These tests were carried out in a cooling test set-up the layout of which is shown in Fig. 7.

Fig. 7: Cooling Test Set-up of Dewar with JT Cooler

The set up employs nitrogen gas filled in a high pressure bottle typically at a pressure of 31.02 MPa with the help of a booster. The gas pressure is then regulated down to a standard value of 20.68 MPa with a line regulator to carry out all the tests at nearly the same input pressure irrespective of the bottle pressure. The gas flow is initiated by operating a solenoid valve electrically, which then enters the JT cooler after passing through the neck filter producing cooling due to Joule Thomson effect.
The fall in temperature at the header level is then recorded using a RTD (Resistance Temperature Device), type Pt-100 (Make: Omega, Model: PR-17) at the place of device so that the inside temperature can be measured. The results in terms of CDT, cold temperature along with the temporal profile of the fall in temperature are correspondingly acquired through a dedicated DAS.

Thereafter, the evaluation of testing of JT cooler with neck filter was carried out. Cold temperature achieved was less than 80K and the cool down time was within 90 secs. Both the results in terms of cool down time (CDT) time and cold temperature achieved were as per required specifications.

5. Conclusions

Infrared (IR) detector cryochambers or Dewars typically operate at cryo-temperatures of ~ 77K and are mostly employed in conjunction with miniature JT cooler assemblies. Usually, JT coolers are beset with issues pertaining to choking and diminished performance in term of the cool down time (CDT) and cold temperatures achieved. Hence, there is a clear need for developing customized neck filters with required porosity and filtering capabilities to achieve continuous desired performance in repeated cool down cycles. A sintered porous neck filter with 5µm pore size and filter porosity of nearly 35% has been successfully developed and duly characterised. Since producing such filters is associated with several development criticalities the involved processes have also been briefly discussed. Further, porous filter developed was assembled at the warm end of the cooler and the cooler assembly was integrated with the IR cryochamber for in system evaluation. The complete assembly was tested in test setup created in the laboratory and the required cryo temperature was achieved in specified cooldown time. This confirmed the desired qualitative and operational specifications of the developed porous filter.

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