The objective of this section is to develop simple, reliable and standardised technique for determining and or predicting porous material properties related to transpiration cooling [66, 67, 68]. The theoretical analysis of woven wire-screen and detailed discussion on friction factor of different screen geometry has been carried out. It also deals with the relationship between primary performance properties, micro-structural characteristic, fabrication methods and parameters for AISI 304 stainless steel compressed and brazed multi-layer woven wire-mesh.

The properties related to transpiration cooling include internal area for heat-transfer within the matrix, the high temperature tensile strength and apparent or effective thermal conductivity.

The search for more suitable porous materials for effective transpiration cooling application in cryogenic rocket engine, led to, stacked and brazed wire-mesh (Rigimesh-Aircraft Porous media Inc) because of its high strength to weight ratio, availability in mesh form, the ease of fabrication and its low cost compared to powder sintered porous media. Also the available material for transpiration cooling such as sintered porous products [66] do not have sufficient strength for application where the operating stresses are very high. Generally, the wire-meshes are woven with considerably more wires in one direction than in the other. In many transpiration cooling applications, the primary stresses are acting in one direction in the plane of the porous wall. In such case it is advantageous to have a porous material that is composed of wires which run parallel to the direction of these primary stresses [58]. As woven, the wire-mesh has a permeability, which is too large for most transpiration cooling applications; however its permeability
which is too large for most transpiration cooling applications; however its permeability can be controlled to any desired degree by brazing the wire-mesh at points where the wires are crossing-over. For desired thickness a number of layers can be stacked and brazed together. The brazing process also increases the stiffness of the bonded wire-mesh and form as an integral plate. The brazing process is explained in more detail separately in Chapter 4. Photo-plates 3.1 and 3.2 illustrate the porous plate manufactured as per new process explained in this thesis.

3.1. CHARACTERISTICS OF WIRE-MESH USED AS POROUS MEDIA

The complex pattern developed for a fluid flow through a brazed wire-mesh (Rigimesh) precludes an exact solution of the equations of motion. Thus it is essential to arrive useful pressure drop correlation via a somewhat less complicated flow model for which theoretical equations can be derived. Here the media is treated as a very thin packed bed. The pressure drop through the wire-mesh is considered to be the sum of both viscous and inertial resistance. However, the viscous resistance predominates in the laminar flow region, where losses are attributable to viscous drag (skin friction at the surface of wires of the medium) and form drag. At high flow rates the effects of the viscous forces are negligible [58], and the inertial losses are assumed to result from turbulent eddies and the losses due to sudden enlargement and sudden contraction of pore cross-section.

In the laminar region, the system is assumed to behave as that of creeping flow around spherical particles. For the case of an isolated spherical particle of radius \( r \) immersed in an infinite continuous fluid, the drag force has been shown by Stokes [69] to be:

\[
F = 6\pi \mu u
\]  
(3.1)
Photo-plate 3.1 Brazed Porous Plate (Rigimesh)

Photo-plate 3.2 Brazed Porous Plate machined ready for use as Injector Faceplate in the Cryogenic Engine
where
\[
\begin{align*}
\mu &= \text{fluid dynamic viscosity, kg m}^{-1}s^{-1} \\
r &= \text{equivalent radius of sphere in meters, m} \\
u &= \text{fluid approach velocity, m s}^{-1} \\
F &= \text{the drag force on single submerged sphere}
\end{align*}
\]

When one considers the force to act independently on each sphere, then the total drag force becomes

\[
F_t = \left[ \frac{3.(1 - P).B}{4\pi r^3} \right] 6\pi \mu ru
\]

(3.2)

Where

\[
\left[ \frac{3.(1 - P).B}{4\pi r^3} \right] = \text{the number of particles in a bed of unit cross-sectional area and}
\]
\[
B = \text{the mesh thickness}
\]
\[
P = \text{porosity}
\]

It is reasonable that in any closely packed system the flow pattern around the individual particles is influenced by interactions with neighbouring particle [70]. This interaction increases as the distance between the particle decreases. As a first approximation, a multiple of the solid volume fraction, C(1-p) is taken as a measure of the degree of interconnection. The total resistive force now becomes

\[
F_r = C.(1 - P) \left[ \frac{3.(1 - P).B}{4\pi r^3} \right] 6\pi \mu r \left( \frac{u}{P} \right)
\]

(3.3)

Where

\[
\left( \frac{u}{P} \right) = \text{the actual free-stream velocity within the packing}
\]
\[
C = \text{a constant}
\]
The force on the fluid must be equal to that produced by a pressure drop $\Delta p$ across the bed thickness. Then, since the free--stream Cross-section of fluid is equal to $P$ [70].

$$\Delta p = C \cdot (1 - P) \left( \frac{3(1 - P)B}{4\pi r^3} \right) 6\pi \mu r \left( \frac{u}{p} \right)$$  \hspace{1cm} (3.4)

Introducing the relationship between $A_i$ and $r$ for spheres

$$\frac{3(1 - P)B}{r}$$  \hspace{1cm} (3.5)

makes the expression general and applicable to non-spherical packing. Equation (3.4) becomes, after rearrangement

$$\frac{\Delta p}{B} = \frac{\alpha}{P^2} \mu A_i \frac{U}{2}$$  \hspace{1cm} (3.6)

Highly turbulent flow through a wire screen looked upon as flow through parallel interconnecting paths of varying cross-sections. As an approximation of the proposed physical mechanism, the pressure drop can be related to the flow conditions through a modification of the relations available for friction losses in circular ducts [71, 72]. For this case since the friction factor for the turbulent flow in ducts is essentially a constant.

$$\frac{\Delta p}{B} = \rho \frac{(U/P)^2}{2d_p} f_0$$  \hspace{1cm} (3.7)

Where

- $f_0$ = value of friction factor
- $d$ = effective diameter of flow path
- $\rho$ = fluid density, Kg m$^{-3}$
Thus
\[ \frac{\Delta P g_c}{B} = \frac{\beta}{P^2 \rho} \frac{u^2}{d_p} \]  (3.8)

when the equations for laminar flow and turbulent flow are added together the resulting equation is
\[ \frac{\Delta P g_c}{B} = \frac{\alpha}{P^2 \mu A^2} U + \frac{\beta}{P^2 \rho} \frac{u^2}{d_p} \]  (3.9)

An implicit assumption is made in this development that the path travelled by the fluid is equal to the thickness of the wire mesh, B. In the case of very complex, tightly woven mesh as twilled Dutch, the fluid path is very tortuous, and the length is longer than B. Therefore the true fluid path length expressed as \( \tau B \) should replace B in equation (3.9). Letting
\[ L = \tau B \]  (3.10)

Where
\[ \tau = \text{tortuosity factor} \]
\[ B = \text{wire mesh thickness} \]
\[ L = \text{true path length of fluid} \]

Rearranging equation (3.9) we obtain the wire mesh friction factor as:
\[ f_0 = \frac{\Delta P g_c P^2 d}{L \rho u^2} = \left( \frac{\alpha / \rho u}{\mu (A^2 d_p)} \right) + \beta \]  (3.11)

Where the ratio of the inertial to the viscous resistance has formed Reynolds number. The viscous and inertial resistance coefficients \( \alpha \) and \( \beta \), were obtained from a non-linear, least squares, regression analysis on the log of the response variable friction factor \( f_0 \), [58]. The values adopted are found to be 8.61 and 0.52 respectively.
The friction factor for flow through porous wire-mesh is

\[ f_o = \frac{\alpha}{R_N} + \beta \]  

(3.13)

Finally the analysis is concluded as the classical friction factor, \( f_o \), for the normal component of flow depends on the Reynolds number [46, 58].

### 3.2 LIMITATIONS OF STOKES LAW

When a body moves through any fluid, it experiences a resistance, \( F \), which acts in the direction opposite to that of the motion of the body. The resistance called the drag, depend on the size of the object, the velocity with which it moves and velocity of the fluid.

G.G. Stokes in 1831, developed an analytical expression for the resistance, \( F \), experienced by a sphere of radius \( r \), moving with a constant velocity \( U \), in a fluid viscosity \( \mu \), is given by as stated in equation (3.1)

\[ F = 6\pi\mu ru \]

This analytical relation is known as Stokes Law, which has been verified experimentally [73] and is found good for values of flow Reynolds number less than 0.2.

Justification of the use of Stoke’s Law in the flow of fluids through the porous specimen is explained in equation (3.1) to (3.13) previously.
3.3 GEOMETRY OF WIRE-MESH

The weave pattern studied is grouped as either plain or Dutch weaves and they are shown schematically in Fig.3.1. As can be seen, the Dutch weaves are tightly woven. In the development of the theory the geometry of wire-mesh is characterised by the parameters screen thickness $B$, specific internal area, $A_i$, for heat-transfer, the mean hydraulic pore diameter, $d_h$, and the porosity, $P$.

The thickness of wire-mesh is determined by averaging a number of micrometer readings taken at various points along its surface. Generally the nominal wire-counts specified by the wire-mesh manufacturer can vary with the actual wire-counts and hence the wire-counts per unit dimension and the wire diameter are determined by the modern photomicrography. Photo-plates 3.3, 3.4, 3.5 and 3.6 illustrates various SEM (Scanning Electron Micrography) photographs used for the above mentioned study. The values of the surface area to unit volume ratio were not determined experimentally, but calculated from derived equations for internal heat-transfer area, $A_i$, based on the assumptions that the woven wires are uniformly cylindrical and they are in point contact. Table 3.1 shows the deviation between the specified and manufacturer's wire-counts and wire diameters on warp and shute directions in wire-meshes.

**Table 3.1**

**WIRE-MESH SPECIFICATION AND ITS DEVIATION IN THE WIRE-COUNTS**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Specified counts wires per 25.4 mm</th>
<th>Measured counts wires per 25.4 mm</th>
<th>Measured wire diameter mm x 10$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n_w$</td>
<td>$n_s$</td>
<td>$n_w$</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>250</td>
<td>51</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>110</td>
<td>24</td>
</tr>
</tbody>
</table>

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Fig. 3.1 CROSS-SECTIONAL VIEW OF WEAVE PATTERNS FOR CERTAIN WIRE-MESHES
Photo-plate 3.3 Photomicrograph for wire counting study.
Photo-plate 3.4 Photomicrograph for wire counts in different magnification
Pore diameters, and all other screen parameters are derivable from the screen wire dimensions, namely the number of warp and shute wires per centimetre and the diameter of warp and shute wires. Table 3.2 shows the tolerance in wire diameters. (Page 75)

With this study a packed bed has been assumed to develop a general correlation applicable to the flow of Newtonian fluids flow though all types of woven metal meshes. The main objective is to study the pressure drop through it. The geometry of the wire mesh is characterised by the parameter, mesh thickness, surface area to volume ratio of wire-mesh, mesh pore diameter and mesh volume void fraction. The theoretical approach arrived here is just as to use a wire mesh as a porous medium for transpiration cooling. Devised techniques are extremely useful to measure wire mesh geometrical properties and aided in the development of equations to calculate mesh parameter such as wire counts, wire diameters, aperture opening, weave patterns or types and pressure drop.

3.4 POROUS MATERIAL DEVELOPMENT METHODOLOGY

Considerable portion of present day material technological effort is being expended on system development to survive high temperature environment [74]. At first transpiration cooling offers one of the most effective cooling methods available for high energy rocket engine combustion and thrust chambers [75]. In this process, coolant passes through a uniform porous wall capillary passage, permitting it to absorb the maximum amount of heat from the solid wall. Because of the porous structure, the metal-to-coolant heat-transfer rate is high [67]. In addition to this, the cooling fluid, discharged into the boundary layer, keeps the mean boundary layer temperature well below that of the hot combustion gases. The success of sweat-cooling for the previously stated rocket propulsion application as for the highly stressed components depends upon the ability to produce a porous material of low, yet closed and controlled porosity, permeability, having a fair resistance to elevated temperatures and possessing the sufficient mechanical properties.
Photo-plate 3.5 Photomicrograph (Rigimesh)
Photo-plate 3.6 Photomicrograph (Rigimesh)
The pressure and temperature distribution in porous material during transpiration cooling depends on mainly two primary properties. They are:

1) Permeability.
2) Thermal conductivity

These two primary properties are in turn dependent on parameters concerning fabrication and micro-structural characteristics of the porous matrices.

The fabrication parameters of a porous structure for an effective mass transfer cooling depend on various factors and the boundary conditions. In these structures the surface exposed to the thermal environment consists of a porous layer through which a high heat absorbing capacity fluid is permeated into the hot side by maintaining pressure difference.

In the present study a porous material of 7.2 mm thickness for injector face plate of LOX/LH₂ propelled rocket engine for transpiration cooling of it is produced by vacuum brazing of wire-woven matrices. A wide range of physical characteristics are availed due to the initial weave geometry, number of layers and brazing process used.

3.5 FABRICATION PARAMETERS OF WIRE-WOVEN MULTILAYER SPECIMEN

The main fabrication parameters of wire-woven porous matrix are:

1) Porosity
2) Permeability
3) Thickness and
4) Strength

Wire-woven meshes are used as raw material for the production of the porous media in the present case. The woven wire meshes are having a definite porosity depending on weaving geometry, wire counts, in shute and warp directions and wire
diameters. These wire meshes are stacked in suitable fixture and brazed in a controlled atmosphere. The brazing alloy will also cause an amount of porosity control by adding a certain volume of it. While staking the wire mesh layers in the fixture, it orients with respect to the aperture of the adjacent mesh, which is applied to control porosity. For each medium this orientation process will be applied differently and hence this also will control the porosity. The brazing will also provide rigidity to the bonded structure as a porous medium with required porosity.

The wire-meshes are woven with considering more wires in one direction than in the other. As woven, the wire-mesh is too permeable for most transpiration cooling applications, but by vacuum brazing a number of layers together, the porous material with high rigidity may be obtained with a wide range of controlled porosity’s and permeability’s, which should cover most requirements for transpiration cooled walls. The rolling of brazed wire-cloth will also cause reduction in thickness. Because both porosity and permeability are functions of the reduction in thickness, it is possible to state the porosity as a function of the permeability coefficient [73].

The required thickness of the porous medium is obtained by adding a number of wire-mesh layers of different thickness while brazing. The thickness of each layer is measured by a micrometer as mentioned earlier. Five thickness measurements were made on each layer, one in the centre and the others 6 mm from the edge of the layer. Prior to brazing, the wire-mesh layers are oriented in the brazing fixture in such a way that every 10° offset is effective between layers mutually. This will also control porosity.

3.6 METHOD OF PRODUCTION OF POROUS MATERIALS

There are various methods adopted for the production of porous materials according to the nature of application and the environment to use. Some of the common methods are mentioned here:

1. Electro-forming technique

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Out of the seven methods mentioned above, the last three only are important for the aerospace application in a high temperature & pressure environment for transpiration cooling.

3.6.1 SINTERING OF METAL POWDERS

Any metal, which can be reduced to a fine powder, can be sintered by mixing with a gas evolving compound under pressure in a reducing atmosphere [38, 76, 77]. The permeability of a given powdered matrix depends on:

1. thickness
2. particle size
3. applied compacting pressure while sintering

The permeability is altered by varying the above three parameters. Because of the relatively low conductivity associated with powdered structures the matrix is generally compacted in mould of the required shape before sintering [78]. Shrinkage of matrix may occur during sintering. This may lead to cracking or control of porosity difficult and they do not possess sufficient strength for application, which requires to handle higher operating stresses [79]. Photo-plate 4.6 shows a nickel powder sintered porous plate. (SIPERM - Federal Republic of Germany).
3.6.2 SINTERING OF WIRE-WOVEN MESHES

A porous medium with requisite porosity can be produced by sintering the clean wire-screens. Woven wire-meshes with a wide range of physical characteristics are available depending on the initial weave pattern, the number of layers and the sintering process adaptability. As stated in earlier chapter, the porosity can be controlled by mutual orientation of the wire-mesh layers. A compacting type sintering die is used for pre-sintering and sintering operations in the chamber. Pre-sintering is to be done in a controlled atmosphere to remove the volatile lubricant binder. After cleaning, the specimen is to be placed again in the die and compacted to the required pressure. Then the pre-loaded compacting die with wire-mesh is loaded in a high vacuum (10^-6 Torr) sintering chamber. Electric heater is to be used as heat source [80]. After specified waiting time, when the compacted wire-mesh material attains super plastic state, the pressure is applied, thus the stacked wire-meshes get bonded strong yielding with required porosity and permeability. If precise control of permeability is required, cold rolling can also be applied. A hot-vacuum sintering furnace with a high capacity press is to be used for sintering work.

3.6.3 VACUUM BRAZING OF COMPACTED WIRE-MESH

Presently available porous materials, such as powder sintered one, does not possess sufficient strength. A wire-woven mesh composed of many layers are compacted and brazed in a controlled atmosphere that can be used as an effective porous media.

According to the weave pattern, there are different types of wire-meshes. Some of the commonly used wire-meshes in aerospace application are illustrated schematically in Fig.3.1. The wire-screen is designated by the number of openings ie, the width in millimetre of the opening or aperture, measured between the inside faces of both warp and shute wires.
3.6.3.1 PLAIN SQUARE WEAVE (PSW)

Woven wire-mesh in which each warp and shute wire passes over one and under the next adjacent complementary wire in both directions.

3.6.3.2 FULL TWILL WEAVE (FTW)

Wire-woven mesh in which each shute wires passes on successively over two and under two warp wires and each warp wire passes successively over and under two shute wires.

3.6.3.3 SEMI TWILL WEAVE (STW) ALSO CALLED CORDUROY

The shute wires are woven as close as possible so as to obtain a "Zero Mesh" ie, a wire cloth practically with out aperture.

3.6.3.4 PLAIN DUTCH WEAVE (PDW)

Woven wire-mesh as the same pattern as a plain weave, except that the warp wires are larger in diameter when compared with the shute wires.

3.6.3.5 TWILLED DUTCH WEAVE (TDW)

It is a combination of twill and Dutch weaves.

All Dutch weaves have a much larger spacing between warp wires than the shute wires, thus enabling the shute wires to be woven much closer and in some cases overlap.
The openings are irregular in shape and their size is to be determined after two cloth is woven.

3.6.3.6  TOLERANCE

A  -  Wire Diameter

Table 3.2
TOLERANCE IN WIRE DIAMETER

<table>
<thead>
<tr>
<th>Diameter between in mm</th>
<th>Tolerance in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3048 - 0.5080</td>
<td>0.0106</td>
</tr>
<tr>
<td>0.232 - 0.2796</td>
<td>0.0076</td>
</tr>
<tr>
<td>0.1143 - 0.2032</td>
<td>0.0064</td>
</tr>
</tbody>
</table>

B  -  Mesh

Tolerances on number of wires per 25.4 mm in warp and shute directions.

For meshes coarser than 200:

\[
\begin{align*}
\text{Warp tolerance} & = 3 \% \\
\text{Shute tolerance} & = 4 \%
\end{align*}
\]

For Meshes Finer Than 200:

\[
\begin{align*}
\text{Warp tolerance} & = 4 \% \\
\text{Shute tolerance} & = 4 \%
\end{align*}
\]