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SOME FLOW PHENOMENA IN A CONSTANT AREA DUCT WITH A BORDA TYPE INLET INCLUDING THE CRITICAL REGION

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ABSTRACT

Mass limiting flow characteristics for a 55 L/D tube with a Borda type inlet have been assessed over large ranges of temperature and pressure (0.68 ≤ T/Tc ≤ 2.3; P/Pc ≤ 3) using fluid nitrogen (Tc = 126.3 K, Pc = 3.417 MPa). Under certain conditions, separation and pressure drop at the inlet was sufficiently strong to permit partial vaporization and the remaining fluid flowed through the tube as if it were a free jet. An empirical relation was determined which defines conditions under which this type of flow can occur. A flow coefficient is presented which enables one to estimate flow rates over the experimental range. A flow rate stagnation pressure map for selected stagnation isotherms and pressure profiles document these flow phenomena.

INTRODUCTION

Flow separation represents a divergence of streamlines from a bounding surface and may or may not be accompanied by a free interface. It represents a common event in fluid dynamics. Airfoils are highly susceptible to separation whether an element of a power system such as a compressor or turbine or an aerodynamic surface of a wing or empennage. In such components separation is undesirable. However in fluid dynamic controls, separation is used advantageously. In fluid circuit logic, separation is used to switch power circuits; in flight, spoilers rapidly decrease lift; and in seals, separation can assist in controlling the loss of the working fluid. In internal flows, one of the most common inlets is sharp edged. However, the inlet most susceptible to separation is the Borda tube. In either case, a vena-contraction is formed and the region of detachment depends on fluid conditions. If the fluid has the potential to vaporize under these circumstances, the problem is substantially more complicated.

While many texts and papers deal with such inlet phenomena, few have addressed the problem of entrance effects on two phase choked flows (1-6) and one addresses the affects at very large L/D (7).

In engineering applications, it is customary to arbitrarily assign a friction factor (L/D) equivalent to account for entrance losses. While this is entirely justified in many problems, it is not for sealing surfaces. In high performance seals, the entrance effects and associated zones of separation cannot be ignored or arbitrarily assigned for they play a major role in seal dynamics; as will be established, entrance conditions can control mass flow and establish pressure distributions for mass limiting flows.

While the material discussed herein is germane to all of the above fields and to separation phenomena, it is primarily applicable to fluid control and dynamics of sealing surfaces. Thus the purpose of this paper is to present flow rate and axial pressure profile data established by mass limiting flows through a 55 L/D straight tube with a Borda type inlet over a large range of stagnation temperatures and pressures including the critical region.

APPARATUS AND INSTRUMENTATION

The basic flow facility was of the blowdown type and is described in detail in Ref. 8. A photograph of the installed test section (fig. 1) illustrates the pressure taps and associated plumbing. The flow was upward, around the U and downward through the test section. The flow rates were metered using a venturi flowmeter located in the bottom of the storage
tank. Inlet stagnation conditions were measured in
the mixing chamber shown immediately behind the scale
in Fig. 1.

The 55 L/D straight 0.483 cm diameter tube test
section consisted of two parts, the Borda type inlet
and a straight tube with a 72° diffuser (see Figs. 1
and 2). A photograph of the Borda type inlet is shown
in Fig. 3. While not a true Borda inlet, the flow
must still experience a reversal prior to entering
the test section.

Eighteen local pressure taps, three stagnation
pressures, and a backpressure were used to establish
the axial pressure profiles. The tap locations are
given in Table I.

The parameters were monitored using a mini-
computer-controlled 15-second update intervals.
At that
time the signals were digitized, recorded, and subse-
sequently reduced using the LeRC data acquisition
system. While the accuracy of the static transducers
was limited to 1/2 percent and the range was large,
systematic calibration and subsequent checks with
higher sensitivity differential pressure transducers
indicated a relative difference of 0.1 percent could
be established and reproduced.

FLOW MODEL AND DISCUSSION

The type of separation phenomena encountered
herein results from a discontinuity in the shape of
the bounding surface. The theoretical inviscid streamlines conform to the bounding surface. No such
conformity to the surface exists with the viscous
flow and separation is initiated. Growth or decay of
this separation, or perturbation, depends on the de-
gree of the discontinuity. The true Borda inlet
causes a full reversal of the streamline at the inlet
and represents the strongest degree of discontinuity
for simple geometries. As such, the incompressible
contraction coefficient\(^1\) of 0.5\(^2\) (9) represents the
most severe separation phenomenon for simple tube in-
lets.

The geometry of the free streamline in potential
flow is found by integrating the real and imaginary
components of \(dz\) (10) (see Fig. 4).

\[
z = x + iy = \frac{1}{V_0} \int V_0 \frac{dz}{\partial y} \, dv
\]

The free streamline can be defined in terms of the
parameter \(\theta\), where \(\theta\) ranges from 0 to \(\pi\):

\[
\chi_0 = \frac{2\chi}{\pi} = -\frac{1}{\pi} \left[ \sin^2 \left( \frac{\theta}{2} \right) + \log \left[ \cos \left( \frac{\theta}{2} \right) \right] \right]
\]

\[
y_0 = \frac{4x}{\pi} = \frac{1}{\pi} \left( 2\pi - \theta + \sin \theta \right)
\]

While the above applies to the two-dimensional
case (Fig. 4(a)), it can be shown that similar stream-
lines exist for the axisymmetric case (10) and the
contraction area or contraction coefficient is still
0.5; \(A_0/A_1 = 1/2\) (Fig. 4(b)), see Ref. 9.

Although the focus of this paper is to provide
characteristic flow and pressure profile data for a
Borda inlet, a model of the flow phenomena is sug-
gested in an attempt to explain the major experimen-
tal finding. A sketch of this model is shown as
Fig. 5.

(1) The entrance contraction is sufficiently
strong to cause separation and vaporization, that is,
the radial velocity is significant and forces separa-
tion resulting in the free streamline some distance
from the wall.

(2) The entrance vortex zone, 2 to 4 diameters
in length, appears to always exist netting up an ini-
tial recompression zone.

(3) Under certain conditions (low temperature,
high pressure fluid) the entrance vortex is suffi-
ciently weak and initiates partial recompression;
usually this recompression is only to the saturation
pressure.\(^3\) The fluid jet then traverses the tube
length with only a small pressure rise.

(4) For the free jet conditions, the vapor and/or
boundary layer growth is assumed to form a diffuser.
This zone may extend through the tube or may not exist
at all.

(5) Strong recompression in the secondary zone
can occur within the tube approaching transition or be
forced on the flow by adjusting the backpressure.
This zone may not exist within the 55 L/D or it may
intersect the initial recompression zone.

(6) Metastable states and normal states of con-
densation and vaporization are assumed to occur.

RESULTS AND DISCUSSION

Pressure Profiles

Typical axial pressure profiles for the 55 L/D
tube with Borda inlet are illustrated as Figs. 6 and
7. For reference purposes, a typical pressure profile
for the gaseous state is given on Fig. 6. Except for
the abrupt nearly two to one characteristic drop at
the inlet followed by recompression, it appears as a
standard friction profile for a tube.

Holding inlet stagnation conditions nearly con-
stant while the backpressure is varied results in the
family of profiles displayed on Fig. 6. At a back-
pressure of 1.69 MPa (245 psia), the pressure profile
near the exit appears monotonically increasing. This is
a transition point where signals that secondary re-
compression is now within the tube. Further increases
in backpressure move the secondary recompression zone
further into the tube until, at sufficiently high back-
pressures the system finally becomes unchoked. Prof-
iles as run 1150 are very difficult to obtain by vary-
ning the backpressure. Secondary recompression
within the duct is most easily established by changing
tagnation conditions. In Fig. 7, recompression is effected along the 117 K isotherm by decreasing the
stagnation pressure from 7.28 MPa (1055 psia) to 5.93
MPa (865 psia). At 7.28 MPa (1055 psia) the initial
recompression is to about 1.48 MPa (215 psia) fol-
lowed by the characteristic monotonic rise in pres-
ure to the exit in the characteristic diffuser zone
(Fig. 6).

At 5.79 MPa (865 psia), the secondary recompre-
sion zone is within the tube and at 5.97 MPa (865
psia) the zone has moved near the initial recompre-
sion zone; note that when the two recompression zones
merge, the initial recompression recovery pressure
equals that of the secondary recompression zone, that
is, more characteristic of the gas profile. One
should note that one transition has occurred, all
profiles merge into a single profile downstream of

\(^1\)For a channel or slot, the ratio of flow width to
channel width; for a tube, \(A_0/A_1\), flow area to tube
area.

\(^2\)The stagnation temperature usually tends to in-
crease over the course of a run due to heating by the
pressurizing gas.

\(^3\)Based on inlet stagnation conditions.

ORIGINAL PAGE IS OF POOR QUALITY.
of the transition point for a given isotherm.

Secondary recompression can be made to take place within the tube by varying the stagnation temperature along an isobar. Along the 10.45 MPa (1515 psia) isobar at 127.8 K, the zone of secondary recompression is greater than 55 L/D, that is, beyond the tube exit, even though the temperature is close to critical. The initial zone of recompression is to about 1.62 MPa (235 psia), followed by the characteristic monotonic rise in pressure through the characteristic diffuser zone. At 127.8 K, which is greater than the critical temperature ($T_c = 126.3 K$), the zone of secondary recompression is within the tube. The initial recompression pressure is to about 2.03 MPa (295 psia). At 130.5 K, the zone has moved further toward the inlet while the pressure in the initial recompression zone has increased to about 2.24 MPa (325 psia). It would appear that the jet cannot be sustained for conditions close to the thermodynamic critical point for 55 L/D. This does not mean that lesser L/D could or could not sustain a jet. In either case, the major control is still near the inlet. To illustrate the magnitude of the pressure effect, inlet stagnation conditions where $P_r = 5.3$ and $T_r = 0.9$ resulted in a reduced pressure in the initial recompression zone of 0.0842 and an average diffuser zone reduced pressure of 0.0686. This represents pressure ratios of 128:1 and 53:1, respectively. Such pressure changes can effect serious instabilities in seals, rotor dynamics, and heat exchangers alike.

One of the major questions now becomes: Is there a way to predict the conditions under which the zone of secondary recompression will occur within the tube? Theoretically not at this time, but empirically an expression was determined as illustrated in Fig. 8. For the inlet stagnation conditions less than this locus, secondary recompression does not occur within the 55 L/D tube.

For conditions above the locus, secondary recompression will occur somewhere within the 55 L/D tube.

An empirical expression for this locus in the present experiment is:

$$P_r = C^2_{12} \left( \frac{T_r}{P_r} \right)^{n}$$

(4)

where

$$C_1 = \frac{C_{15}}{D}$$

(5)

Equations (4) and (5) are written in the above form because it is expected that the constant $C_1$ depends on the flow area $A$, which in this case was 55, and surface roughness $\varepsilon$. For these tests the tube was smooth honed with emery paper.

Flow Rate

Reduced flow rate data as a function of reduced stagnation pressure for selected isotherms are given as Fig. 9. Attempts to predict these flow rates theoretically were unsuccessful, so the authors resorted to standard flow coefficient techniques. By calculating the isentropic nonequilibrium two-phase choked flow rate according to the model of Henry and Paunke\(^4\) (11), one can define a flow coefficient as:

$$C_0(P_r, T_r) = \frac{g_{data} / C}{g_r / C} = \frac{g_r}{g_r}$$

(6)

As can be seen from Fig. 10, the coefficient of

\(^4\)Charts of the ideal isentropic flows are available in Ref. 12.

Eq. (5) is strongly dependent on reduced temperature, increasing from about 0.54 at $T_r = 0.67$ to 0.8 at $T_r = 1.2$; its value then decreases to 0.73 for the gas. Further, it is weakly dependent on pressure away from the saturation locus. At the saturation locus the nonequilibrium model predicts $C_r$ values less than the locus of Fig. 10, see isolated points of Fig. 9, which may be two phase. Between $T_r = 0.9$ and 1.0, the data appear to reach a plateau followed by an abrupt rise.

So by calculating the isentropic flow rate using the nonequilibrium model and applying the flow coefficient (Fig. 10), the flow rate for this configuration can be determined at any temperature or pressure including the critical region. While the effect of secondary recompression on the pressure profiles is very significant, little change in the flow rate can be found using Eq. (5) and comparing data with the theoretical curves of Ref. 12. This, of course, implies that the mass limiting effect occurs at the inlet, not at the exit.

Fluid properties for evaluating $C_r$ were obtained using the computer code established in Ref. 13.

SUMMARY

Some flow characteristics in a constant area duct with a Borda type inlet, as may be found in some seals, applications and boilers, have been assessed over a wide range of temperature and pressure (0.68 $\leq T_c \leq 2.3$; $P_r / P_c \leq 3$) with fluid nitrogen. ($T_0 = 126.3 K$, $P_0 = 3.417 MPa$). The 55 L/D test section with Borda inlet has a Borda diffuser at the exit.

Under certain conditions, separation at the inlet was sufficiently strong to permit the fluid to flow through the tube as if it were a free jet; in these cases, the diffuser zone extended to the physical diffuser and secondary recompression did not occur within the tube. Otherwise some combination of the initial recompression - diffuser - secondary recompression zones occurred within the tube. In the critical region the diffuser zone vanishes. An empirical criterion was established to determine when secondary recompression would occur within the tube.

The flow coefficient ($C_0 / C_r$) varied nonlinearly with temperature from 0.54 at $T_r = 0.67$ to 0.8 at $T_r = 1.2$, for the gas ($T_r = 2.3$). The coefficient is weakly dependent on pressure except near saturation where the coefficient tends to unity. Moreover, at a reduced stagnation pressure $P_r / P_c = 3.1$ and reduced temperature of 0.68 the average axial reduced pressure was 0.0688, over a 50:1 change. The ratio of the stagnation pressure to the initial recompression zone pressure was over 125:1.

Flow rates for selected isotherms and pressure profiles are presented for this configuration to document these flow phenomena.

**SYMBOLS**

- $A$: area, cm$^2$
- $B$: slot or channel width, cm
- $C_r$: constant of Eq. (5)
- $C_0$: flow coefficient, Eq. (6)
- $D$: tube diameter, cm
- $G$: flow rate, g/cm$^2$-s
$Q_r$ reduced flow rate

$Q^*$ flow normalizing parameter, $\sqrt{P_0^2 / \gamma}$

$6030$ g/cm$^2$-s, for nitrogen

$L$ tube length, cm

$P$ pressure, MPa

$P_r$ reduced pressure, $P/P_0$

$R$ gas constant, MPa-cm$^3$/g-K

$T$ temperature, K

$T_r$ reduced temperature, $T/T_0$

$V$ specific volume, cm$^3$/g

$V_0$ velocity parameter

$W$ complex potential

$X$ distance, cm

$x_0$ dimensionless distance

$Y$ distance, cm

$y_0$ dimensionless distance

$Z$ compressibility, $P/V_T$

$z$ complex coordinate, cm

$\theta$ parameter

$\rho$ density, g/cm$^3$

$e$ surface roughness ratio

$\delta$ boundary layer thickness, cm

Subscripts:

c. critical

I isentropic

0 stagnation

REFERENCES


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!Table 1. Pressure Tap Locations for 85 L/D Tube with Borda Type Inlet (See Fig. 2)

<table>
<thead>
<tr>
<th>Pressure tap</th>
<th>Location</th>
<th>Pressure tap</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_0$ Mixing chamber</td>
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<td>-2.5</td>
<td>-1</td>
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<tr>
<td>$P_{10}$</td>
<td>$P_{11}$</td>
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<td>-0.5</td>
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<tr>
<td>$P_{12}$</td>
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<td>-125</td>
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<td>0.32</td>
<td>125</td>
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<tr>
<td>$P_{14}$</td>
<td>$P_{15}$</td>
<td>0.64</td>
<td>125</td>
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<td>$P_{15}$</td>
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<td>$P_{18}$</td>
<td>6.1</td>
<td>2</td>
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<tr>
<td>$P_{18}$</td>
<td>$P_{19}$</td>
<td>Immediately upstream of backpressure control valve</td>
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*At Borda inlet.
Figure 1. - Apparatus.
Figure 2 - Schematic of 55L/D test section with borda type inlet. See table I for pressure tap locations.
Figure 3. - Borda inlet.
Figure 4. - Schematic for theoretical streamlines for a borda inlet.

Figure 5. - Suggested model for 55 L/D straight tube with borda type inlet.
Figure 6. - Typical pressure profiles - axial position 55 L/D straight tube with Borda inlet.
<table>
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<tr>
<th>RUN</th>
<th>$q/S$</th>
<th>$P_0$ (MPa)</th>
<th>$P_0$ (psia)</th>
<th>$T_0$ (K)</th>
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<td>86.2</td>
</tr>
</tbody>
</table>

$1600$

10.45 MPa (1315 psia) STAGNATION ISOBAR

117 K STAGNATION ISOTHERM

130.5 K

10.34 MPa (1315 psia) STAGNATION ISOBAR

121.7 K

117 K STAGNATION ISOTHERM

Figure 7. - Typical pressure profiles - axial position 55 L/D straight tube with Borda inlet.
Figure 8. - Flow transition region as a function of reduced pressure and temperature for Borda inlet =55 L/D straight tube - $T_R \leq 1$. Fluid nitrogen.

Figure 9. - Reduced flow rate as a function of reduced pressure for selected isotherms. Borda inlet =55 L/D straight tube.
Figure 10. Reduced flow rate ratio versus reduced temperature for 55 L/D straight tube with a Borda inlet. Fluid nitrogen. (\(\square\) two phase).
Mass limiting flow characteristics for a 55 L/D tube with a Borda type inlet have been assessed over large ranges of temperature and pressure (0.68 ≤ T/T_c ≤ 2.3; P/P_c ≤ 3) using fluid nitrogen (T_c = 126.3 K, P_c = 3.417 MPa). Under certain conditions, separation and pressure drop at the inlet was sufficiently strong to permit partial vaporization and the remaining fluid flowed through the tube as if it were a free jet. An empirical relation was determined which defines conditions under which this type of flow can occur. A flow coefficient is presented which enables one to estimate flow rates over the experimental range. A flow rate stagnation pressure map for selected stagnation isotherms and pressure profiles document these flow phenomena.