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ABSTRACT

LOX and LN_2 data for two-phase critical flow through nozzles have been acquired with precision control. The principal measured parameters were inlet conditions, critical flow rate and critical flow pressure ratio. The data conclusively demonstrate that the principle of corresponding states can be applied to two-phase choked flow through nozzles. These data also demonstrate that the proper normalizing parameters have been developed and current theories can provide an adequate means for extrapolating to other fluids.

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SUMMARY

LOX and LN_2 data for two-phase critical flow through nozzles has been acquired with precision control. The principle measured parameters were inlet conditions, critical flow rate and critical flow pressure ratio. The reduced critical flow rate data for LOX and LN_2 as a function of reduced pressure for selected isotherms are in excellent agreement; the theoretical lines serve as a reference. The reduced critical pressure ratio data are shown as a function of reduced pressure, for two isotherms. Again, the theory serves as a reference but the agreement between the LOX and LN_2 data for this highly sensitive measurement is excellent. The data conclusively demonstrate that the principal of corresponding states can be applied to two-phase choked flow through nozzles. These data also demonstrate that the proper normalizing parameters have been developed and current theories can provide an adequate means for extrapolating to other fluids.

SYMBOLS

A	Area, cm^2
D	Diameter, cm
G	Mass flux, gm/cm^2-sec
L	Length, cm
P	Pressure, MN/cm^2
R	Radius, cm
S	Entropy, joule/gm-K

X	Axial distance, cm
Z	Compressibility factor, . . .
ρ	Density, gm/cm^3

Subscripts

c	Thermodynamic critical conditions
o	Stagnation conditions
R	Reduced parameters, P/P_c etc.
t	Throat conditions

INTRODUCTION

The general field of two-phase choked flow has been well surveyed by Hsu (ref. 1), Henry et al. (ref. 2), and Smith (ref. 3). However, to the knowledge of the present authors, no experimental data have been reported on two-phase choked flow of liquid oxygen. The choked flow of liquid nitrogen in converging-diverging nozzles has been extensively mapped (refs. 4, 5). Reference 5 includes an evaluation of existing theories for two-phase choked flow in the subcooled region. Other flow geometries have been examined (refs. 6, 7, and 8) and finally the relationship between various fluids has been explored (refs. 9, 10).

Hendricks and Simoneau (ref. 9) using nitrogen and methane data demonstrated that two-phase choked flow rates could be normalized to reduced coordinates by the parameter

$$G^* = \sqrt{\frac{\rho_c P_c}{Z_c}} \tag{1}$$

The paper also showed that if the choked flow pressure ratio, P_t/P_o, were plotted in the same reduced coordinates

$$P_R = \frac{P_o}{P_c} \tag{2}$$

$$T_R = \frac{T_o}{T_c} \tag{3}$$

the nitrogen and methane data would reduce to a single curve. This implied that the extensive work done with nitrogen could be applied to oxygen. The present experiment was undertaken to demonstrate that the corresponding states normalization (Eq. 1), is applicable to oxygen. The high level of control on the experimental flow parameters made possible a comparison between oxygen and nitrogen data with considerable precision.

APPARATUS AND PROCEDURE

A schematic of the test facility, which is basically a blow-down system, is shown in figure 1. Prior to loading LOX (or LN_2) the system was purged with helium gas. LOX (or LN_2) was transferred from the supply dewar into the high pressure dewar, and the liquid level monitored using temperature sensors T_1 to T_4. GOX (or GN_2) was used to force the LOX (or LN_2) out of the dewar through the venturi flowmeters into the test section and finally out the vent to atmosphere.

One of the unique features of this facility was the real time data reduction and display with a separate data record mode. The transducer signals were computer processed and temperatures, pressure, flow rates and reduced parameters were displayed on TV monitors. The TV display was updated at 1 Hz to give us precise visual control over the variables.

Several steps were required to take a data point. Approximate inlet conditions (P_o, T_o) were established by permitting a small flow through the back pressure valve while at the same time bubbling large quantities of GOX (or GN_2) through the LOX (or LN_2) in the tank. With the inlet pressure (P_0) held fixed by an automatic control valve, nozzle choking was established when two different back pressures resulted in no change in mass flow rate. The precise isotherm was then set by simultaneously coordinating the temperature, pressure and flow parameters on the TV display with the bubbling rate of GOX (or GN_2) through the fluid in the tank. Then with no bubbling, the system stabilized and data were recorded.

TEST SECTION

The axisymmetric converging-diverging nozzle used in this experiment is shown in cross-section in figure 2. The pertinent dimensions are given in Table 1. The stagnation temperature was measured using platinum sensors in the mixing chamber, immediately upstream of the test section. The stagnation pressure was also measured in the mixing chamber and designated as P_6 in figure 1. This test section was also used in reference 5.

RESULTS

The experiment covered a range in reduced stagnation temperature isotherms T_0/T_c from 0.61 to 1.67 with reduced stagnation pressure P_0/P_c ranging from near saturation to 2.

The most significant result of this experiment is the acquisition of liquid oxygen (LOX) data along the exact reduced isotherms as the liquid nitrogen (LN_2) data, (see figs. 3 and 4). These selected data isotherms for choked flow rate (G/G^*) and pressure ratio (P_t/P_0) of oxygen and nitrogen all agree to within ±0.3 K along the given isotherm. An examination of figure 3 shows that in reduced coordinates the data for LOX and LN_2 agree exactly, even in the areas where some anomalous behavior appears which may be due to nozzle geometry. The theoretical lines (refs 4, 5) serve only as a reference, since the data are our major concern.

The use of G^*, (Eq. 1), as a normalizing parameter to relate oxygen and nitrogen choked flow rate data seems clearly established; likewise the use of corresponding states parameters does reduce the pressure ratio data to single sets of isotherms, over the range of data reported here.

While current theories (e. g., isentropic equilibrium for $S \geq S_0$ and isentropic nonequilibrium for $S < S_0$) do not precisely predict these choked flow results (solid lines (figs. 3 and 4)) they do provide an adequate engineering means for extrapolating to other fluids. For more precise work, departures from data must be used to correct the extrapolation, or one could use the data directly.

CONCLUSIONS

The experiment was conducted to obtain liquid oxygen and liquid nitrogen data in order to evaluate the use of corresponding states parameters in two-phase choked flow of subcooled fluids. From our data, it can be concluded that both the flow rate and pressure ratio data of subcooled oxygen and nitrogen can be normalized in a corresponding states manner. The normalizing parameter for the flow rate is

$$G^* = \sqrt{\frac{\rho_c P_c}{Z_c}}$$

Current theories on two phase choked flows can provide an adequate engineering means for extrapolating to other fluids. For more precise work, the data must be used.

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TABLE 1. - CONICAL CONVERGING-DIVERGING

NOZZLE DIMENSIONS (IN CM.)

Overall length		31.1
Throat diameter		0.3555±0.0007
Area (cm^2)		0.09926
Length constant area section		1.135±0.020
L/D		3.20
Radius of curvature		1.77
Pressure tap diameter		0.051
Convergence half angle, degrees	$6.790^{\circ} \pm 0.05$	6.790±0.05
	or	
Divergence half angle, degrees	$3.780^{\circ} \pm 0.23$	3.780±0.23

TAP LOCATIONS (Referenced to Throat)

Tap no.	X	R	A/A_t	
0	-9.12	-----	∞	(inlet plenum)
1*	-5.062	0.645	13.18	
2*	-3.066	0.408	5.26	
3*	-2.263	0.312	3.08	
4	-1.984	0.279	2.46	
5	-1.692	0.244	1.88	
6	-1.052	0.178	1.00	
7	-0.536	0.178	1.00	
8	-0.185	0.178	1.00	
9	0.112	0.185	1.08	
10	0.455	0.208	1.37	
11*	0.940	0.240	1.82	
12*	1.933	0.306	2.95	
13*	7.943	0.703	15.61	
14	12.939	1.033	33.73	
15*	17.943	1.363	58.79	
B*	22.0	-----	∞	(outlet plenum)

*Note: These taps were not connected for this experiment

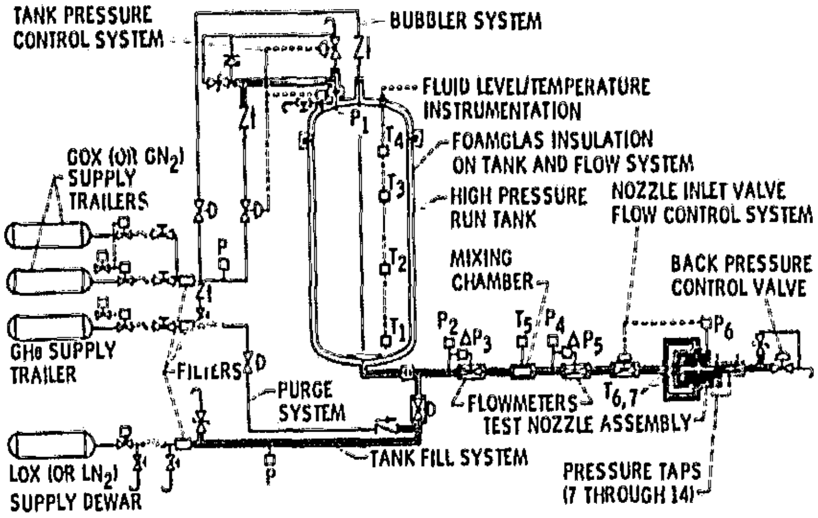

Figure 1. - LOX choked flow test system.

Figure 2. - Conical convergence test section.

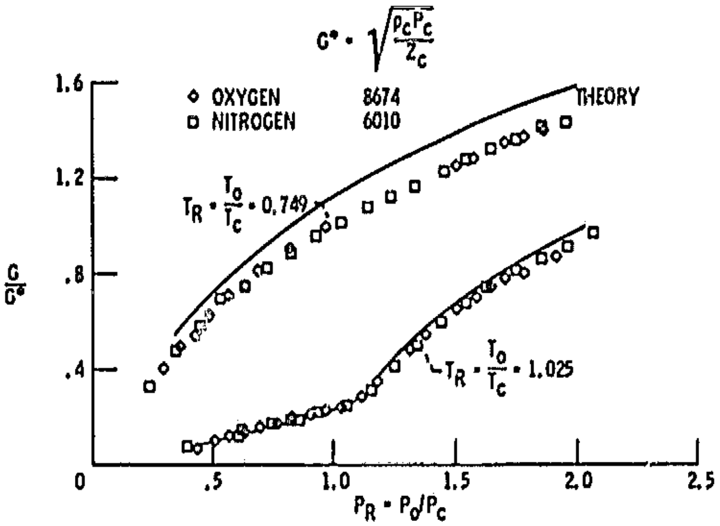

Figure 3

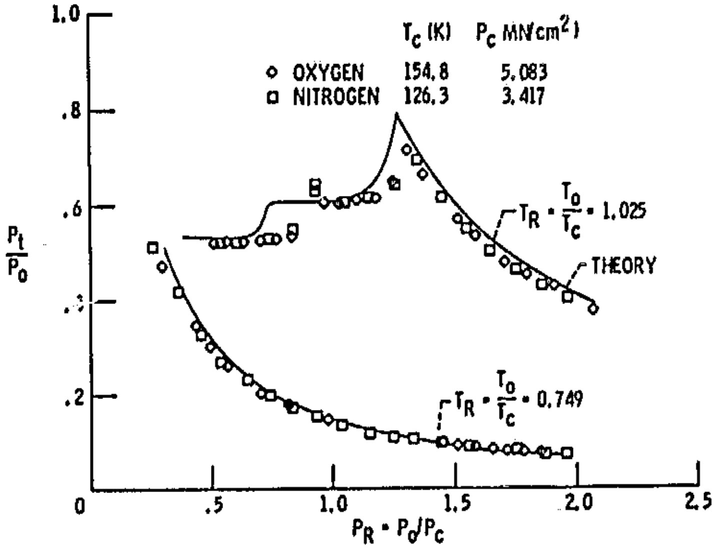

Figure 4

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