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EFFECT OF ENTRY OF SUBCOOLED CRYOGEN ON THERMAL STRATIFICATION IN A CRYOGENIC STORAGE TANK

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ABSTRACT

The purpose of this study was to predict if subcooled cryogenic liquid entering the bottom of a storage tank will destroy the thermal stratification of the tank.

After an extensive literature search, a formula for maximum critical Reynolds Number which used to predict the destratification of a cryogenic tank was found. Example of calculations and graphics to determine the mixing of fluid in the tank were presented.

SUMMARY

1. Formula of Critical Reynolds number to predict destratification was shown.

2. Graphs of Reynolds number of inlet flow pipe, and critical Reynolds number versus different inlet pipe diameter were presented.

3. A sample of calculation of liquid hydrogen tank, and conclusion was given.

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1. INTRODUCTION

1.1 BACKGROUND

Thermal stratification exists in cryogenic fluid in a storage tank when there is a temperature differential between fluids on the top and the bottom of the storage tank. This temperature differential is caused by the buoyant forces resulting from the density difference between hot and cold fluid. Because of the buoyant forces, it is evident that some degree of stratification exist in almost all cryogenic storage tanks unless there is a mixing force.

This study involved a cryogenic refrigeration subcooling systems which take liquid from the top of a cryogenic storage tank and passed it through a refrigerator and back into the bottom of the tank. Figure 1 shows a schematic of piping connecting the storage tank. In order to make the refrigeration process more efficient the system should provide as high a temperature difference between the cryogen at the inlet and outlet of the refrigerator as possible. Mixing of the fluid in the tank would lower the temperature of the cryogen going into the refrigerator and lower the temperature difference. This study was made to determine how to analyze the effect of subcooled liquid entering the bottom of the tank on thermal stratification in the tank.

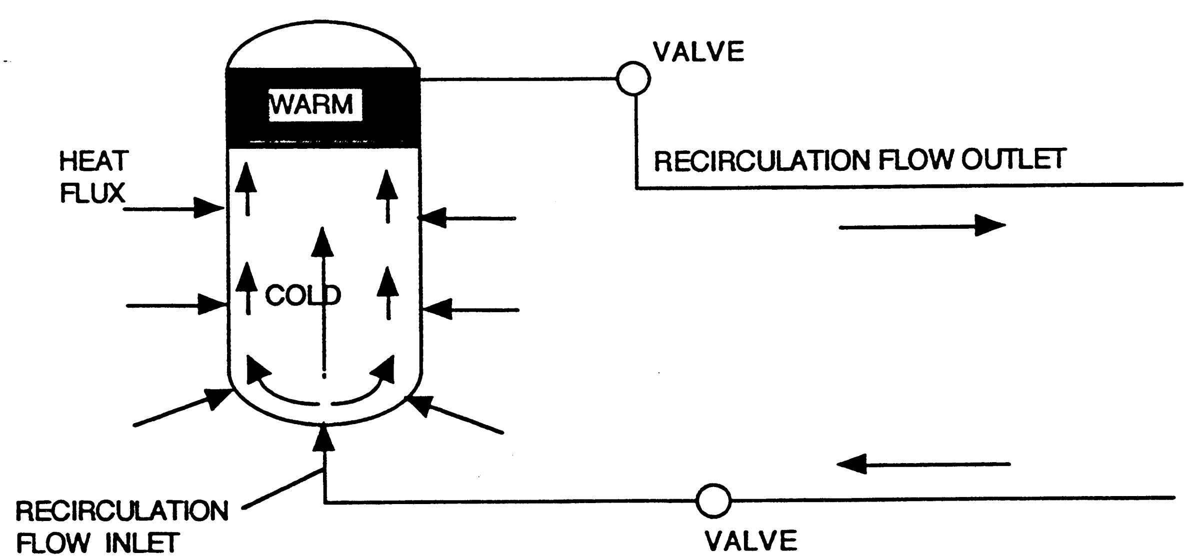

Fig. 1 Schematic of Cryogenic Tank System

1.2 OBJECTIVE

The object of this study was to gather applicable engineering information and data and see if cryogen entering the bottom of a cryogenic storage tank, will cause the hot and cold liquid to mix. The cryogenic liquids studied were liquid oxygen and liquid hydrogen. Typical tank sizes were selected.

2. CALCULATIONS

2.1 CRITICAL REYNOLDS NUMBER AND REYNOLDS NUMBER

A critical Reynolds number of the inlet flow pipe was defined in reference [3] as that value where the buoyant force of tank liquid becomes unimportant. For a Reynolds number greater than this critical value, the system may be assumed to mix completely. Below this critical Reynolds number, the buoyant forces may be strong enough to limit the degree of mixing. The critical Reynolds number was given by a correlation available in reference [3].

The critical Reynolds number is given by

$$\mathrm{Re}^2 = 0.912\left(\frac{D}{H}\right)^{\frac{2}{3}} \mathrm{Pr}^{\frac{-2}{3}} Gr^{*\frac{2}{3}} \qquad (1)$$

where Re = Critical Reynolds number of inlet pipe

Pr = Prandtl number

D = Tank diameter

H = Tank height

Gr* = Modified Grashof number

The modified Grashof number is given in reference [3] as

$$Gr^* = \frac{g\beta q'' L^4}{k v^2} \qquad (2)$$

where: g = Gravitational acceleration

β = Coefficient of thermal expansion of liquid

q" = Heat flux

L = Liquid height

k = Thermal conductivity of liquid

ν = Kinematic viscosity of liquid

The Reynolds number is given as

$$Re = \frac{Vd}{\nu^2} \qquad (3)$$

where V = Flow velocity

d = Inside diameter of inlet pipe

ν = Kinematic viscosity

2.2 SAMPLE OF CALCULATION

2.2.1 THE CRITICAL REYNOLDS NUMBER FOR LIQUID HYDROGEN

The critical Reynolds number for liquid hydrogen is calculated from data given in Table 1. Pressure, temperature, and heat flux are assumed.

TABLE 1 **LH2 Tank**

Term	Symbol	Unit	Value	Reference
Pressure in tank	p	psia	35	
Outlet temperature	To	R	27	
Tank diameter	D	ft.	10	
Tank height	H	ft.	37.75	
Tank volume	Vt	ft^3	2669	

TABLE 1 (Continued)

Term	Symbol	Unit	Value	Reference
Inside dia. of inlet pipe.	d	ft.	0.5	
Inlet flow rate	Q	ft^3 /hr.	1299.5	
Thermal expansion	β	1/R	0.006256	[1]
Density	ρ	lbm/ft^3	4.758	[1]
Specific heat	Cp	Btu/lbm. R	1.6595	[1]
Dynamic viscosity	μ	lbm/ft. hr.	0.0539	[1]
Thermal conductivity	k	Btu/ft.hr.R	0.04795	[1]
Prandtl number	Pr		1.867	[1]
Heat flux	q"	Btu/hr. ft^2	14.23	
Kinematic viscosity	v	$ft.^2$/hr.	0.01133	[1]
Tank liquid height	L	ft.	34.5	
Tank liquid volume	Vl	ft^3	2562	
Gravitation acceleration	g	$ft./hr^2$	417,312,000	

From Equation (2)

$$Gr* = \frac{g\beta L^4 q''}{kv^2} = \frac{4.173(10^8)\frac{ft}{hr^2}(6.256)(10)^{-3}\left(\frac{1}{R}\right)(34.5)^4 ft^4 (14.23)\frac{Btu}{ft^2 hr}}{4.795(10)^{-2}\frac{Btu}{hr.ft.R}\left((1.133)(10)^{-2}\right)^2\frac{ft^4}{hr^2}}$$

$Gr* = 8.549 \times 10^{18}$

From Equation (1)

$$\mathrm{Re}^2 = 0.912\left(\frac{D}{H}\right)^{\frac{2}{3}} \mathrm{Pr}^{\frac{-2}{3}} Gr*^{\frac{2}{3}}$$

$$\mathrm{Re} = \left[0.912\left(\frac{10}{37.75}\right)^{\frac{2}{3}}(1.867)^{\frac{-2}{3}}\left[8.549(10)^{18}\right]^{\frac{2}{3}}\right]^{\frac{1}{2}}$$

Re (Critical Reynolds number) = 1.0256 x 10^6

(for the selected tank with D = 10 ft, H = 37.75 ft and L = 34.5 ft.)

2.2.2 THE CRITICAL REYNOLDS NUMBER AND REYNOLDS NUMBER FOR LIQUID OXYGEN

The calculation for Critical Reynolds number and Reynolds numbers at different inlet pipe diameters are shown in the Appendix section.

3. RESULTS AND CONCLUSION

3.1 RESULTS

The Critical Reynolds number and Reynolds number for both liquid hydrogen and liquid oxygen are calculated by using the Microsoft Excel spreadsheet are completed (see Appendix). Graphs of critical Reynolds number and Reynolds number versus inlet pipe diameter for both LH2 and LO2 are shown in Fig. 2 and Fig. 3.

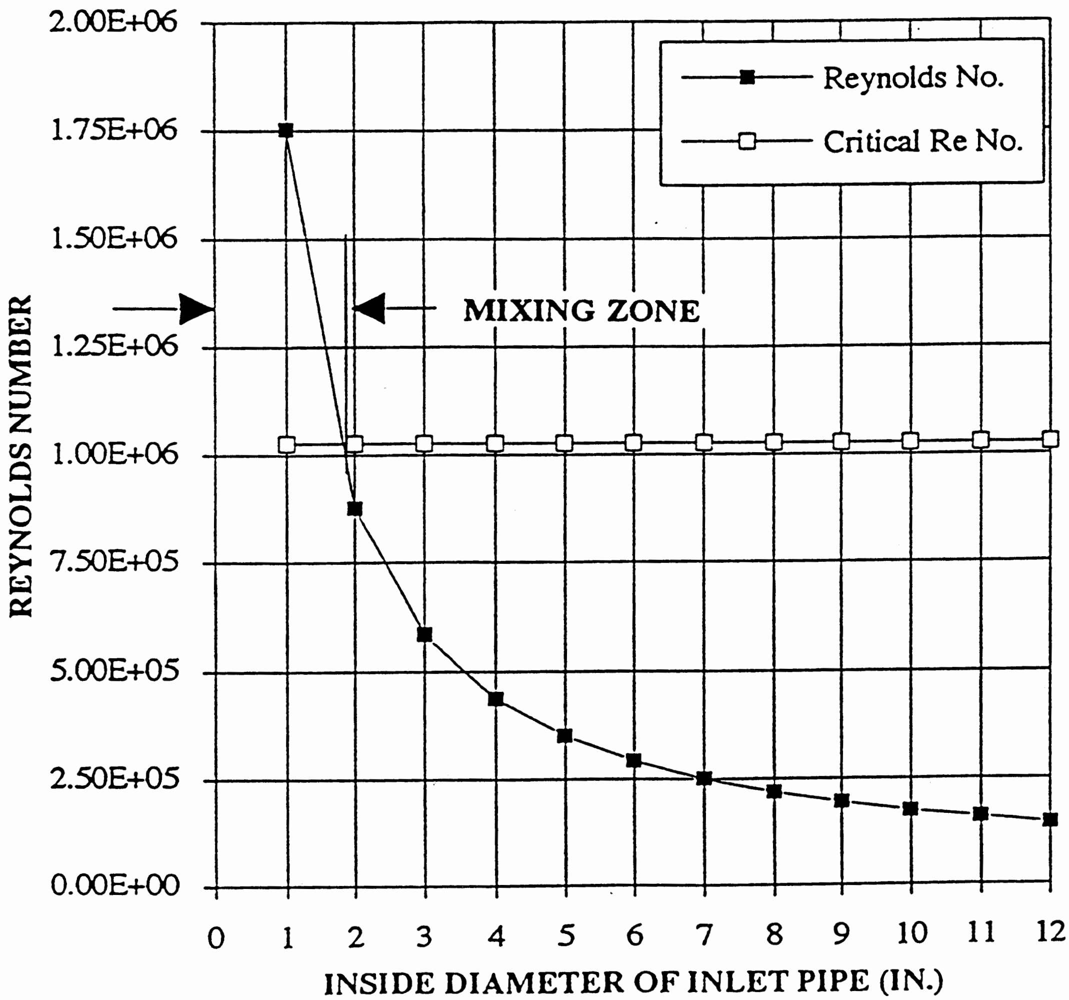

Fig. 2 Liquid Hydrogen Tank Mixing Curve

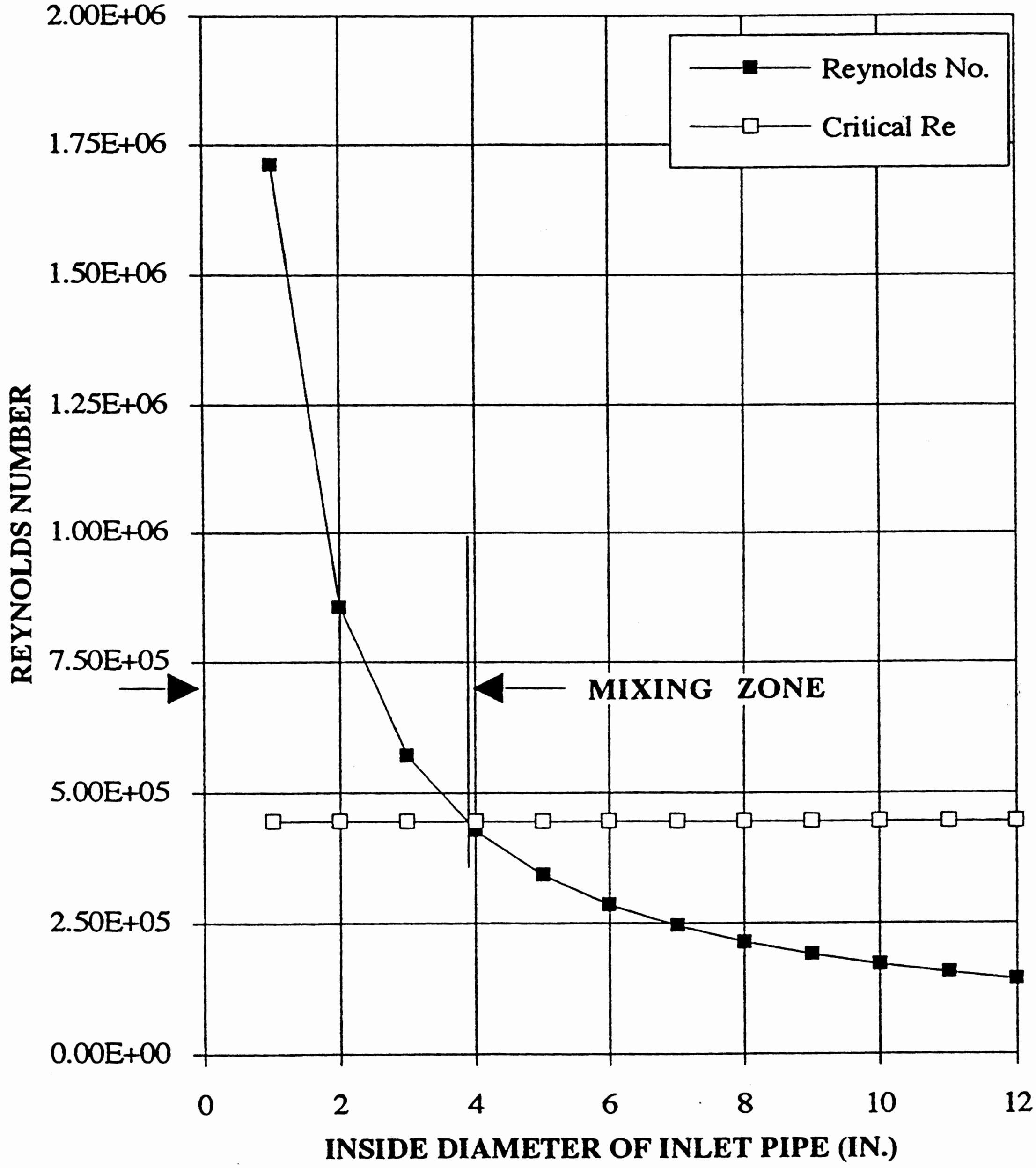

Fig. 3 Liquid Oxygen Tank Mixing Curve

3.2 CONCLUSION

In conclusion, form Fig. 2, it indicates that for liquid hydrogen tank an inlet pipe diameter of about 1.8 in. or less, the tank fluid will have a complete mix. Diameter of the inlet pipe greater the 1.8 in will be large enough to prevent complete mixing.

Fig. 3 indicates that for liquid oxygen tank an inlet pipe diameter of about 4 in. or less, the tank fluid will have a complete mix. Diameter of the inlet pipe greater the 4 in. will prevent complete mixing.

The dimensions of the selected hydrogen tank are D = 10 ft., H = 37.75 ft., and L = 34.5 ft.

The pressure and temperature at the tank inlet were assumed to be 25 psia and 27 R respectively.

The dimensions of the selected oxygen tank are D = 10 ft., H = 23.83 ft., and L = 21.22 ft.

The pressure and temperature at the tank inlet were assumed to be 35 psia and 141 R respectively.

Results shown in this report are used as a guide to place a reasonable prediction only.

REFERENCES

[1] Robert D. McCarty. *Hydrogen Technological Survey - Thermophysical properties.* NASA S-3089, National Aeronautics and Space Administration, Washington, D.C. 1975.

[2] Hans M. Roder and Lloyd A. Weber. *ASRDI Oxygen Technology Survey, Volume I: Thermophysical Properties,* NASA SP-3071, National Aeronautics and Space Administration, Washington, D.C. 1972.

[3] T. M. Lovrich and S. H. Schwartz. *Development of Thermal Stratification and Destratification Scaling Concepts - Volume I, Definition of Thermal Stratification Scaling Parameters and Experimental Investigations*, NASA CR-143944, NASA George C. Marshall Space Center, Marshall Space Center, Alabama, October 1975.

APPENDIX

CALCULATION OF MODIFIED GRASHOF NUMBER

Formula:

$$GR* = \frac{g\beta q'' L^4}{kv^2}$$

CALCULATION OF CRITICAL REYNOLDS NUMBER

Formula:

$$\mathrm{Re}^2 = 0.912\left(\frac{D}{H}\right)^{\frac{2}{3}} \mathrm{Pr}^{\frac{-2}{3}} Gr*^{\frac{2}{3}}$$

TABLE 1 LIQUID HYDROGEN TANK

Term	Symbol	Unit	Value	Reference
Pressure	p	psia	35	
Outlet temperature	To	R	27	
Tank diameter	D	ft.	10	
Tank height	H	ft.	37.75	
Tank volume	V	cu ft.	2669	
Inside dia. of inlet pipe.	d	ft.	0.5	
Inlet flow rate	Q	cu ft./hr.	1299.5	
Thermal expansion coefficient	β	1/R	0.006256	[1]
Density	ρ	lbm/cu ft.	4.758	[1]
Specific heat	Cp	Btu/lbm. R	1.6595	[1]
Dynamic viscosity	μ	lbm/ft. hr.	0.0539	[1]
Thermal conductivity	k	Btu/ft.hr.R	0.04795	[1]
Prandtl number	Pr		1.867	[1]
Heat flux	q"	Btu/hr. sq ft.	14.23	
Kinematic viscosity	v	sq ft./hr.	0.01133	[1]
Tank liquid height	L	ft.	34.5	
Tank liquid volume	Vt	cu ft	2562	
Gravitation acceleration	g	ft./sq hr	417,312,000	

LH2 Tank

Modified Grashof number

$$Gr^* = 8.549 \times 10^{18}$$

Critical Reynolds number of the LH2 tank with selected D, H, and L

$$Re = 1.0256 \times 10^{6}$$

Data for curve in Fig. 2

Inside Pipe Diameter (in.)	Area (sq ft.)	velocity (ft/s)	Reynolds No.	Critical Re No.
1	5.45E-03	6.62E+01	1.75E+06	1.03E+06
2	2.18E-02	1.65E+01	8.76E+05	1.03E+06
3	4.91E-02	7.35E+00	5.84E+05	1.03E+06
4	8.73E-02	4.14E+00	4.38E+05	1.03E+06
5	1.36E-01	2.65E+00	3.50E+05	1.03E+06
6	1.96E-01	1.84E+00	2.92E+05	1.03E+06
7	2.67E-01	1.35E+00	2.50E+05	1.03E+06
8	3.49E-01	1.03E+00	2.19E+05	1.03E+06
9	4.42E-01	8.17E-01	1.95E+05	1.03E+06
10	5.45E-01	6.62E-01	1.75E+05	1.03E+06
11	6.60E-01	5.47E-01	1.59E+05	1.03E+06
12	7.85E-01	4.60E-01	1.46E+05	1.03E+06

TABLE 2 LIQUID OXYGEN TANK

Term	Symbol	Unit	Value	Reference
Pressure	p	psia	35	
Outlet temperature	To	R	140.5	
Tank diameter	D	ft.	10	
Tank height	H	ft.	23.83	
Tank volume	V	cu ft.	1589	
Inside dia. of inlet pipe	d	ft.	0.4	
Tank inlet flow rate	Q	Cu ft./hr.	1026.74	
Thermal expansion coefficient	β	1/R	0.02167	[2]
Density	ρ	lbm/cu ft.	74.99	[2]
Specific heat	Cp	Btu/lbm. R.	0.4	[2]
Dynamic viscosity	μ	lbm./ft. hr.	0.687	[2]
Thermal conductivity	k	Btu/ft.hr.R.	0.09685	[2]
Prandtl number	Pr		2.837	[2]
Heat flux	q"	Btu/hr.sq ft.	29.681	
Kinematic viscosity	ν	Sq ft./hr.	0.00916	[2]
Tank liquid height	L	ft.	21.215	
Tank liquid volume	Vl	Cu ft.	1525.44	
Gravitation acceleration	g	ft./sq hr	417,312,000	

LO2 Tank

Modified Grashof number

$$Gr^* = 6.691 \times 10^{17}$$

Critical Reynolds number of LO2 tank with selected D, H, and L

$$Re = 4.4468 \times 10^{5}$$

Data for curve in Fig. 3

Inside Pipe Diameter (in.)	Area (sq ft.)	Velocity ft./s	Reynolds No.	Critical Re
1	5.45E-03	5.23E+01	1.71E+06	4.45E+05
2	2.18E-02	1.31E+01	8.56E+05	4.45E+05
3	4.91E-02	5.81E+00	5.71E+05	4.45E+05
4	8.73E-02	3.27E+00	4.28E+05	4.45E+05
5	1.36E-01	2.09E+00	3.43E+05	4.45E+05
6	1.96E-01	1.45E+00	2.85E+05	4.45E+05
7	2.67E-01	1.07E+00	2.45E+05	4.45E+05
8	3.49E-01	8.17E-01	2.14E+05	4.45E+05
9	4.42E-01	6.46E-01	1.90E+05	4.45E+05
10	5.45E-01	5.23E-01	1.71E+05	4.45E+05
11	6.60E-01	4.32E-01	1.56E+05	4.45E+05
12	7.85E-01	3.63E-01	1.43E+05	4.45E+05