

Cryogenic Fluid Management (CryoFM) Tool for Systems Analysis and Design



Presented By
Matt Moran

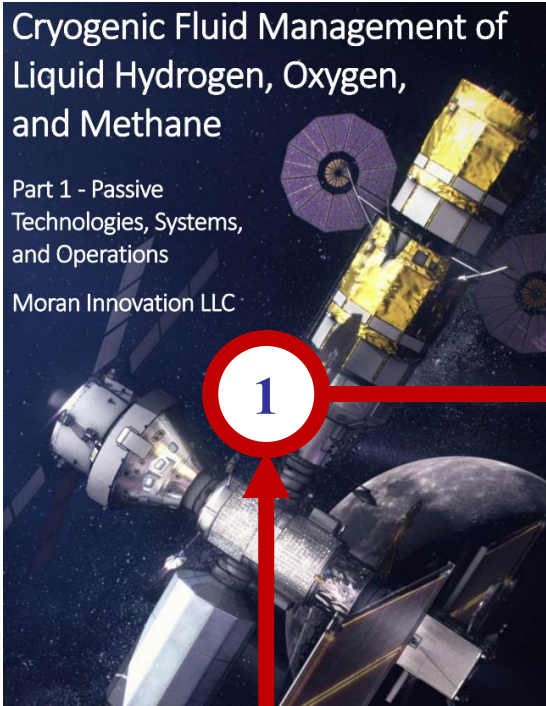
matt@moraninnovation.com

Thermal & Fluids Analysis Workshop
TFAWS 2022
September 6th-9th, 2022
Virtual Conference

Cryogenic Fluid Management of Liquid Hydrogen, Oxygen, and Methane

Part 1 - Passive Technologies, Systems, and Operations

Moran Innovation LLC



CryoFM™ - Cryogenic Fluid Management - Passive (v1.3.1)

Moran Innovation ?

1.0 Introduction
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[NIST fluid properties](#)
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[Desktop version CP](#)
[Bond & Reynolds #s](#)
[Raleigh & Nusselt #s](#)

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[Solid conduction](#)
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4.0 Venting
[Vent losses](#)

Defined Constants

Absolute zero temp (T ₀):	-273.15 C
Std atmosphere (atm):	101.325 kPa
Earth std gravity (g ₀):	9.80665 m/s ²
Stefan-Boltzmann (σ):	5.6704E-08 W/m ² ·K ⁴

Unit Conversions

Acceleration

3.217E+01 ft/s ²	=	9.807E+00 m/s ²
9.807E+00 m/s ²	=	3.217E+01 ft/s ²
3.217E+01 ft/s ²	=	1.000E+00 g
9.807E+00 m/s ²	=	1.000E+00 g

Area

1.00E+00 m ²	=	9.290E-02 m ²
9.290E-02 m ²	=	1.000E+00 ft ²

Conductivity, thermal

3.455E-01 Btu/hr-ft-F	=	5.980E-01 W/m-K
5.980E-01 W/m-K	=	3.455E-01 Btu/hr-ft-F

Density

6.240E+01 lbm/ft ³	=	9.995E+02 kg/m ³
9.995E+02 kg/m ³	=	6.240E+01 lbm/ft ³

Diffusivity, thermal

1.567E-06 ft ² /s	=	1.456E-07 m ² /s
1.456E-07 m ² /s	=	1.567E-06 ft ² /s

Energy

1.000E+00 Btu	=	1.055E+03 J
---------------	---	-------------

Goal: A public domain tool for performing system level first-order calculations for common cryogenic fluid management topics (no CUI, ITAR, nor classified data)

Objectives:

1. Report series documenting key calculations and contextual information
2. Integrated Excel workbook for interactive calculations (online & desktop versions)
3. VBA user defined functions for custom system calculations and Excel add-in
4. Python functions for Jupyter notebooks and other supported platforms & apps
5. Eventually... importable Python library

1

2

5

import CryoFM

4

3

```

File Edit Selection View Go Run Terminal Help • CryoFM.py - Visual Studio Code
EXPLORER
C:\Users\moran> OneDrive - Moran Innovation LLC \Software Dev \CryoFM \CryoFM.py
CryoFM.py
CryoFM.py
NO FOLDER OPENED
OUTLINE
TIMELINE
CryoFM.py
1 from CoolProp.CoolProp import PropsSI
2
3
4 # CoolProp the physical property evaluation
5
6
7 def f(density_liquid, density_vapor, acceleration, diameter_freesurf,
8     name, variable1_name, variable1_value, variable2_name, variable2_value, vari
9
10
11 # D
12
13
14 def bond(density_liquid, density_vapor, acceleration, diameter_freesurf
15     return (density_liquid-density_vapor)*acceleration*(diameter_fre
16
17
18 def reynolds(density, speed, length, viscosity_dynamic):
19     return density*speed*length/viscosity_dynamic
  
```

```

Microsoft Visual Basic for Applications - [modCryoFM (Code)]
Project - VBAProject
CoolProp (CoolProp.xlam)
Solver (Solver.xlam)
Microsoft Excel Objects
modCryoFM
References
References to CoolProp.xlam
Properties - modCryoFM
Alphabetic Categorized
(Name) modCryoFM
[General]
Function BondNumber(density_liquid, density_vapor, acceleration, diameter_freesurf,
BondNumber = (density_liquid - density_vapor) * acceleration * diameter_freesurf /
End Function
Function ReynoldsNumber(density, speed, length, viscosity_dynamic)
ReynoldsNumber = density * speed * length / viscosity_dynamic
End Function
Function FillFraction(density_liquid, volume_tank, density_vapor, volume_tank)
FillFraction = (volume_tank - volume_tank * density_vapor / density_liquid) /
End Function
Function MassLiquid(density_liquid, volume_tank, density_vapor, volume_tank)
MassLiquid = density_liquid * volume_tank * (1 - fill_fraction)
End Function
Function MassGas(density_vapor, volume_tank, density_gas, volume_tank)
MassGas = density_vapor * volume_tank * fill_fraction
End Function
Function VaporizedLiquid(mass_liq_init, enthalpy_liq_init, enthalpy_liq_final,
VaporizedLiquid = mass_liq_init * (enthalpy_liq_final - enthalpy_liq_init) /
End Function
  
```


CryoFM™ - Cryogenic Fluid Management - Passive (v1.4.1)

[HOME](#) [Reference Report](#)
[NIST fluid properties](#)

Descriptive Title of calculations	User inputs (yellow)			Link to this help sheet
Variable	[user input]	units	comment	
Variable	[user input]	units	comment	
Fluid	Oxygen	----	Use values below	
Fluid property	[property value]	units	[user property input]	
Fluid property	[property value]	units	[user property input]	
Output result	[result value]	units	comment	

[1] Footnote...

Calculation results (green) fluid props (blue) User props input (if online or no CoolProps)

Verification Case

Variable	[user input]	units	comment [1]
Variable	[user input]	units	comment
Fluid	Oxygen	----	Use values below
Fluid property	[property value]	units	[user property input]
Fluid property	[property value]	units	[user property input]
Output result	[result value]	units	comment

Verification case (gray)

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To get started using CryoFM, click on the "HOME" link above (top left). If you're using the online version and inadvertently try typing in a cell that isn't for user input, the tool may stop responding. If that happens, simply refresh your browser to reset the tool.

Cryogenic Fluid Management of Liquid Hydrogen, Oxygen, and Methane

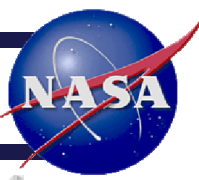
Part 1 - Passive Technologies, Systems, and Operations

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CryoFM: Online Home and Reference Report Contents



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Home Energy Space Defense IP/Publications Training Contact

CryoFM™ - Cryogenic Fluid Management - Passive (v1.4.1)



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1.456E-07 m ² /s	=	1.567E-06 ft ² /s

Energy

1.000E+00 Btu	=	1.055E+03 J
1.055E+03 J	=	1.000E+00 Btu

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CryoFM: Online Calc Sheet and Report Section Examples



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[NIST fluid properties](#)



Bond Number		
Pressure (P)	2.00E+05 Pa	vapor pressure [1] [2]
Acceleration (a)	9.81E-06 m/s ²	induced or environment
Diameter, liquid (D _{fs})	6.600 m	liquid free surface
Fluid	Oxygen ---->	Use values below
Temp, saturated (T _{sat})	97.24 K	97.23553533
Density, liquid (ρ _l)	1.105E+03 kg/m ³	1105.40119
Density, vapor (ρ _v)	8.354E+00 kg/m ³	8.354467802
Surface tension (σ)	1.141E-02 N/m	0.011405531
Bond number (Bo)	41	Eqn 1.1
Reynolds Number		
Characteristic dim (L)	0.100 m	e.g. hydraulic diameter
Flow speed (u)	1.000E+01 m/s	average
Pressure (P)	2.00E+05 Pa	static
Temp, fluid (T _b)	97.00 K	bulk
Fluid	Oxygen ---->	Use values below
Density (ρ)	1.107E+03 kg/m ³	1106.635129
Visc, dynamic (μ)	1.639E-04 Pa-s	1.639E-04
Reynolds number (Re)	6.75E+06	Eqn 1.2

[1] Partial pressure of the vapor at the liquid-gas interface

[2] Properties evaluated at liquid-gas interface conditions

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The Bond number (*Bo*) is the ratio of acceleration to capillary forces and is given by:

$$Bo = \frac{(\rho_l - \rho_v) \bar{a} D_{fs}^2}{\sigma}$$

Bond number (1.1)

Where ($\rho_l - \rho_v$) is the density difference between the liquid and vapor phases, (\bar{a}) is the local acceleration, (D_{fs}) is the liquid free surface diameter, and (σ) is surface tension. Bond number provides characterization of the fluid free surface shape and can be used to calculate the propulsive force needed to settle the fluid in a reduced gravity environment.

Figure 1.8 illustrates an example of the free surface shape of a fluid in a cylindrical tank as a function of Bond number.

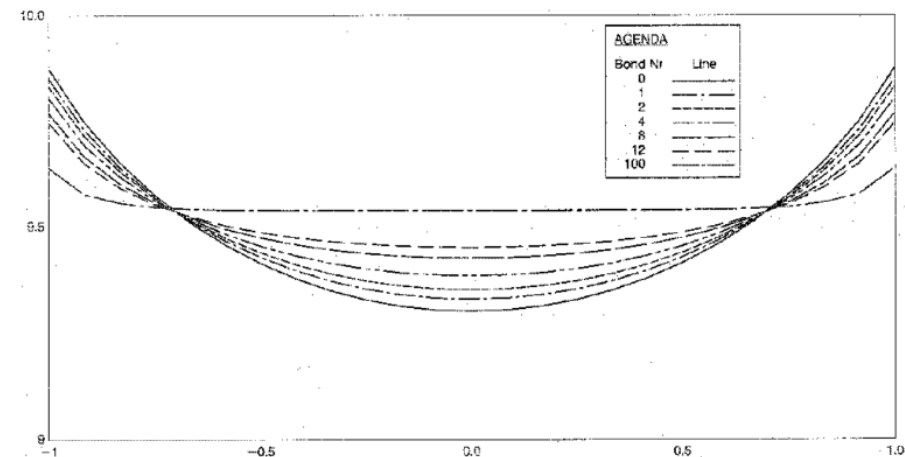
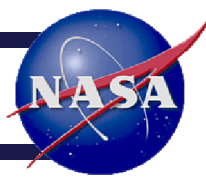


Figure 1.8 Meridian of the free surface for different Bond numbers in a cylindrical tank²¹



CryoFM: Desktop Version with CoolProp



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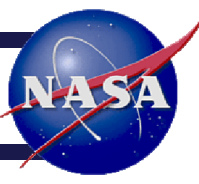
Specific State Points		CoolProp variables
Pressure (P)	2.000E+05 Pa	P
Temperature (T)	76.1 K	T
Fluid	Oxygen (phase determined by state point)	
Conductivity (k)	1.711E-01 W/m-K	conductivity
Density (ρ)	1.209E+03 kg/m ³	Dmass
Diffusivity, thermal (α)	8.43029E-11 m ² /s	conductivity/Dmass/C
Expansion coeff (β)	3.856E-03 1/K	isobaric_expansion_coeff
Enthalpy (h)	-1.570E+05 J/kg	Hmass
Internal energy (u)	-1.572E+05 J/kg	U
Sp heat, p=const (C _p)	1.679E+03 J/kg-K	C
Sp heat, v=const (C _v)	9.873E+02 J/kg-K	Cvmass
Visc, kinematic (ν)	2.460E-07 m ² /s	viscosity/Dmass
Saturation Conditions		
Pressure (P)	2.000E+05 Pa	P
Fluid	Oxygen ---->	liquid
Temperature, sat (T _{sat})	97.24 K	T
Density, sat (ρ_{sat})	1.105E+03 kg/m ³	Dmass
Enthalpy, liquid (h _l)	-1.213E+05 J/kg	Hmass
Enthalpy, vapor (h _v)	8.448E+04 J/kg	Hmass
Heat of vaporiz (h _{fg})	2.057E+05 J/kg	ΔH (liquid to vapor)
Surface tension (σ)	1.141E-02 N/m	surface_tension
Sp heat, sat (C _{sat})	1.717E+03 J/kg-K	T*(dS/dT) _{sat}
Boil-off		
Boil-off rate per watt	1.75E+01 g/hr/W	no sensible heating

Verification Case

Specific State Points		CoolProp Variables
Pressure (P)	200000 Pa	P
Temperature (T)	76.12 K	T
Fluid	Oxygen (depends on state point)	
Conductivity (k)	0.171089634 W/m-K	conductivity
Density (ρ)	1208.978117 kg/m ³	Dmass
Diffusivity, thermal (α)	8.43029E-08 m ² /s	conductivity/Dmass/C
Expansion coeff (β)	0.003855827 1/K	isobaric_expansion_coefficient
Enthalpy (h)	-157032.9927 J/kg	Hmass
Internal energy (u)	-157198.4216 J/kg	U
Specific heat (C _p)	1.678660356 J/kg-K	C
Sp heat, v=const (C _v)	987.2642184 J/kg-K	Cvmass
Visc, kinematic (ν)	2.45958E-07 m ² /s	viscosity/Dmass
Saturation Conditions		CoolProp Variable
Pressure (P)	200000 Pa	P
Fluid	Oxygen liquid	Q = 0
Temperature, sat (T _{sat})	97.23553533 K	T
Density, sat (ρ_{sat})	1105.40119 kg/m ³	Dmass
Enthalpy, liquid (h _l)	-121260.0881	Hmass
Enthalpy, vapor (h _v)	84481.32336	Hmass
Heat of vaporiz (h _{fg})	205741.4114 J/kg	ΔH (liquid to vapor)
Surface tension (σ)	0.011405531 N/m	surface_tension
Sp heat, sat (C _{sat})	1716.922341 J/kg-K	T*(dS/dT) _{sat}
Boil-off		
Boil-off rate per watt	17.49769273 g/hr/W	no sensible heating



CryoFM: VBA and Python Function Examples



```
Microsoft Visual Basic for Applications - [modCryoFM (Code)]
File Edit View Insert Format Debug Run Tools Add-Ins Window Help
(BondNumber) BondNumber
Function BondNumber(density_liquid, density_vapor, acceleration, diameter)
    BondNumber = (density_liquid - density_vapor) * acceleration * (diameter)
End Function
Function ReynoldsNumber(density, speed, length, viscosity_dynamic)
    ReynoldsNumber = density * speed * length / viscosity_dynamic
End Function
Function FillFraction(mass_liquid, density_liquid, volume_tank)
    FillFraction = mass_liquid / volume_tank / density_liquid
End Function
Function MassLiquid(fill_fraction, density_liquid, volume_tank)
    MassLiquid = density_liquid * volume_tank * fill_fraction
End Function
Function MassGas(fill_fraction, density_gas, volume_tank)
    MassGas = density_gas * volume_tank * (1 - fill_fraction)
End Function
Function VaporizedLiquid(mass_liq_init, enthalpy_liq_init, enthalpy_liq_final)
    VaporizedLiquid = mass_liq_init * (enthalpy_liq_final - enthalpy_liq_init)
End Function
```

```
File Edit Selection View Go Run • CryoFM.py - Visu... CryoFM.py
CryoFM.py
C:\Users> Users > moran > OneDrive - Moran Innovation LLC > Software Dev > CryoFM > CryoFM.py
1 from CoolProp.CoolProp import PropsSI
2
3
4 # CoolProp thermophysical property evaluation
5
6
7 def fluid_property(property_name,variable1_name,variable1_value)
8     return PropsSI(property_name,variable1_name,variable1_value)
9
10
11 # Dimensionless numbers
12
13
14 def bond(density_liquid,density_vapor,acceleration,diameter)
15     return (density_liquid-density_vapor)*acceleration*(diameter)
16
17
18 def reynolds(density,speed,length,viscosity_dynamic):
19     return density*speed*length/viscosity_dynamic
20
21
```



CryoFM: Jupyter Notebook Example (Python)



jupyter CryoFM (autosaved)



Logout

File Edit View Insert Cell Kernel Widgets Help

Trusted

Python 3 (ipykernel)

Code

Dimensionless Numbers

Thermophysical Properties Evaluation with CoolProp

```
In [2]: ▶ import CoolProp.CoolProp as CP
```

Reynolds Number

```
In [3]: ▶ length = 0.1 # m
```

```
In [4]: ▶ velocity = 10 # m/s
```

```
In [5]: ▶ fluid = 'Oxygen'
```

```
In [6]: ▶ temp = 97 # K
```

```
In [7]: ▶ pressure = 2E5 # Pa
```

```
In [8]: ▶ density = CP.PropsSI('D','T',temp,'P', pressure,fluid) # kg/m^3
```

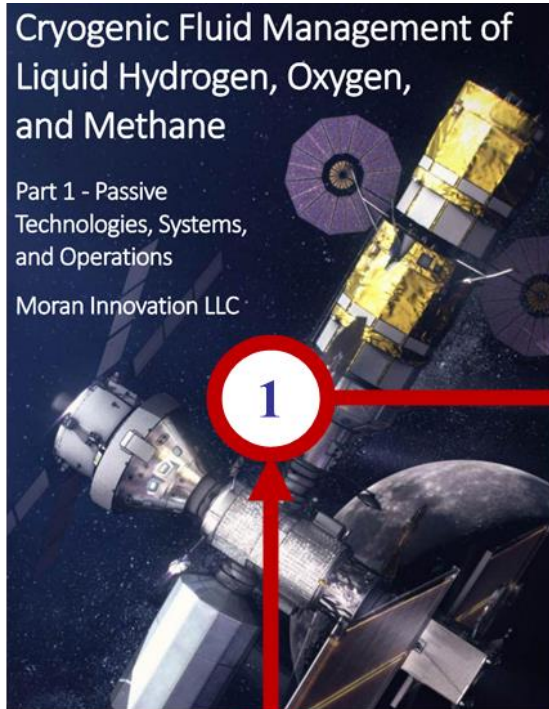
```
In [9]: ▶ visc_dynamic = CP.PropsSI('V','T',temp,'P', pressure,fluid) # Pa-s
```

```
In [10]: ▶ Reynolds = density*velocity*length/visc_dynamic
```

```
In [11]: ▶ print("{:e}".format(Reynolds))
```

```
6.752322e+06
```


Status and Forward Plans



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9.807E+00 m/s ²	= 3.217E+01 ft/s ²
3.217E+01 ft/s ²	= 1.000E+00 g
9.807E+00 m/s ²	= 1.000E+00 g
Area	
1.00E+00 m ²	= 9.290E-02 m ²
9.290E-02 m ²	= 1.000E+00 ft ²
Conductivity, thermal	
3.455E-01 Btu/hr-ft-F	= 5.980E-01 W/m-K
5.980E-01 W/m-K	= 3.455E-01 Btu/hr-ft-F
Density	
6.240E+01 lbm/ft ³	= 9.995E+02 kg/m ³
9.995E+02 kg/m ³	= 6.240E+01 lbm/ft ³
Diffusivity, thermal	
1.567E-06 ft ² /s	= 1.456E-07 m ² /s
1.456E-07 m ² /s	= 1.567E-06 ft ² /s
Energy	
1.000E+00 Btu	= 1.055E+03 J

1. Passive CFM report complete and available [online](#); active CFM report planned next; systems modeling, applications, and others after that
2. Excel desktop and online versions under active development; beta testing planned ([email](#) if interested)
3. VBA user defined functions under active development; Excel add-in planned
4. Python functions under active development; Jupyter notebook examples planned
5. Importable Python library planned

1

2

5

import CryoFM

4

3

```

File Edit Selection View Go Run Terminal Help
CryoMpy - Visual Studio Code
EXPLORER
CryoMpy
C:\Users\moran> OneDrive - Moran Innovation LLC \Software Dev \CryoFM > CryoMpy
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2
3 # CoolProp the physical property evaluation
4
5
6
7 def f...
8
9
10
11
12
13
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15     return (density_liquid-density_vapor)*acceleration*(diameter_fre
16
17
18 def reynolds(density,speed,length,viscosity_dynamic):
19     return density*speed*length/viscosity_dynamic
    
```

```

Microsoft Visual Basic for Applications - modCryoFM (Code)
Project: VBAProject
General
Function BondNumber(density_liquid, density_vapor, acceleration, d
    BondNumber = (density_liquid - density_vapor) * acceleration *
End Function
Function ReynoldsNumber(density, speed, length, viscosity_dynamic)
    ReynoldsNumber = speed * length / viscosity_dynamic
End Function
Function FillFraction(density_liquid, volume_tank)
    FillFraction = volume_tank / density_liquid
End Function
Function MassGas(density_gas, volume_tank)
    MassGas = density_gas * volume_tank
End Function
Function VaporizedLiquid(mass_liq_init, enthalpy_liq_init, enthalp
    VaporizedLiquid = mass_liq_init * (enthalpy_liq_final - enthal
End Function
Properties - modCryoFM
modCryoFM Module
Alphabetic: Categoryed
[Name] modCryoFM
    
```



Some Online Resources

- [Cryogenic Fluid Management of Hydrogen, Methane and Oxygen](#)
- [Engineering Analysis and Modeling](#)
- [Hydrogen Systems Development: Past, Present and Future](#)
- [Adaptive Systems Approach for Breakthrough Innovations \(ASABI\)™](#)
- [Densified Liquid Hydrogen and No-Loss \(Zero Boil-off\) Systems](#)

A graphic for MORAN INNOVATION LLC featuring a dark blue world map with city lights. The text 'MORAN INNOVATION LLC' is written in large, white, bold, sans-serif capital letters across the center of the map.

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CREATING BREAKTHROUGH POWER AND PROPULSION SYSTEMS