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

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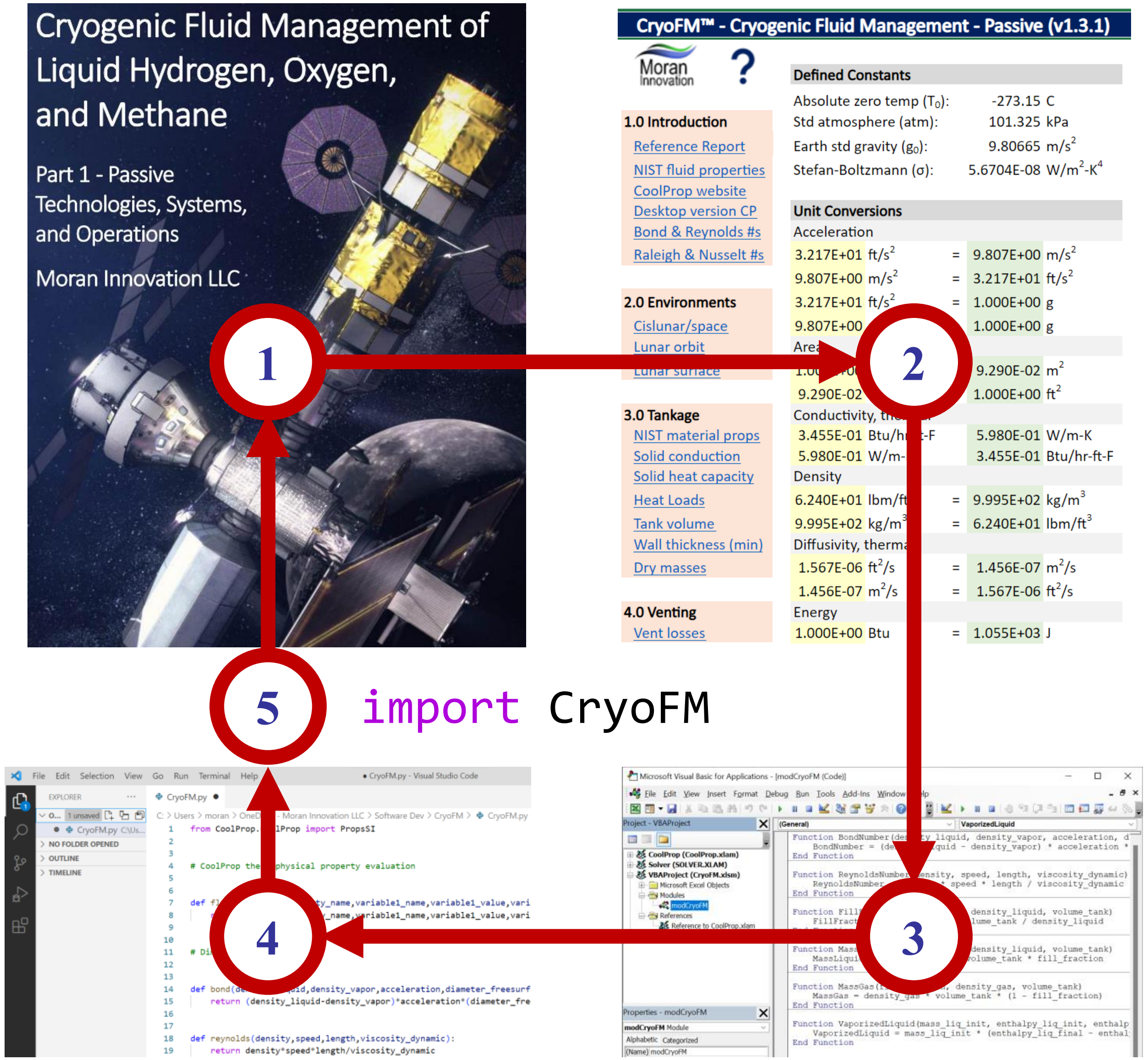
CryoFM Goal and Objectives

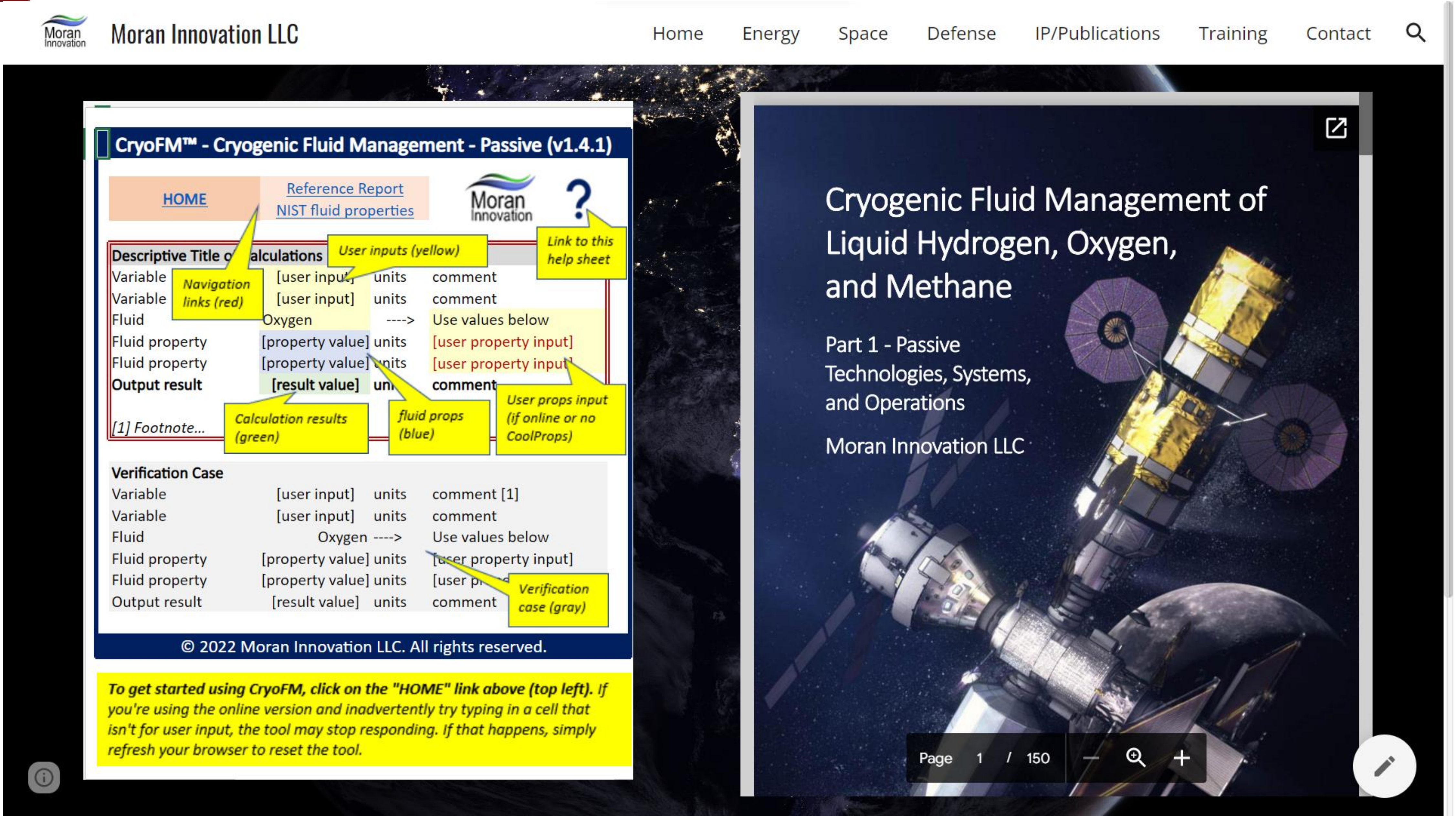


Goal: A public domain tool for performing system level first-order calculations for common cryogenic fluid management topics (no CUI, ITAR, nor classified data)

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

CryoFM: Online Startup View



CryoFM: Online Home and Reference Report Contents

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

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1.0 Introduction
- Reference Report
- NIST fluid properties
- CoolProp website
- Desktop version CP
- Bond & Reynolds #s
- Raleigh & Nusselt #s

2.0 Environments
- Cislunar/space
- Lunar orbit
- Lunar surface

3.0 Tankage
- NIST material props
- Solid conduction
- Solid heat capacity
- Heat Loads
- Tank volume
- Wall thickness (min)
- Dry masses

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

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CryoFM: Online Calc Sheet and Report Section Examples

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

HOME | Reference Report | 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

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

$$Bo = \frac{(\rho_l - \rho_v)\bar{a}D_{fs}^2}{\sigma} \qquad \text{Bond number } \mathbf{(1.1)}$$

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.

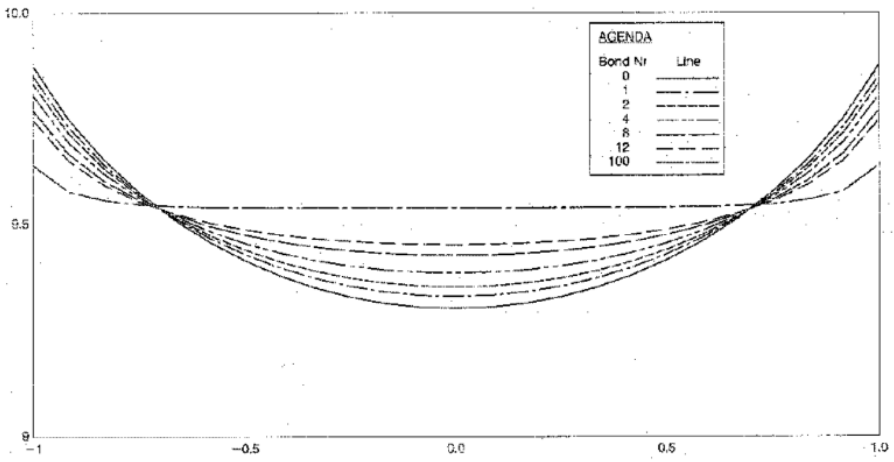

Figure 1.8 Meridian of the free surface for different Bo numbers in a cylindrical tank[21]

CryoFM: Desktop Version with CoolProp

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HOME | Reference Report | NIST fluid properties

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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_coeffi
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/m3	Dmass
Diffusivity, thermal (α)	8.43029E-08	m2/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 (Cv)	987.2642184	J/kg-K	Cvmass
Visc, kinematic (ν)	2.45958E-07	m2/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/m3	Dmass
Enthalpy, liquid (hl)	-121260.0881		Hmass
Enthalpy, vapor (hv)	84481.32336		Hmass
Heat of vaporiz (hfg)	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)]

```vba
Function BondNumber(density_liquid, density_vapor, acceleration, diamete
    BondNumber = (density_liquid - density_vapor) * acceleration * (diam
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_
    VaporizedLiquid = mass_liq_init * (enthalpy_liq_final - enthalpy_liq
End Function
```

CryoFM.py

C: > Users > moran > OneDrive - Moran Innovation LLC > Software Dev > CryoFM > CryoFM.py

```python
from CoolProp.CoolProp import PropsSI


# CoolProp thermophysical property evaluation


def fluid_property(property_name,variable1_name,variable1_va
    return PropsSI(property_name,variable1_name,variable1_va


# Dimensionless numbers


def bond(density_liquid,density_vapor,acceleration,diameter_
    return (density_liquid-density_vapor)*acceleration*(diam


def reynolds(density,speed,length,viscosity_dynamic):
    return density*speed*length/viscosity_dynamic


```

CryoFM: Jupyter Notebook Example (Python)

jupyter CryoFM (autosaved)

Logout

File Edit View Insert Cell Kernel Widgets Help

Trusted | Python 3 (ipykernel)

Run 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
```

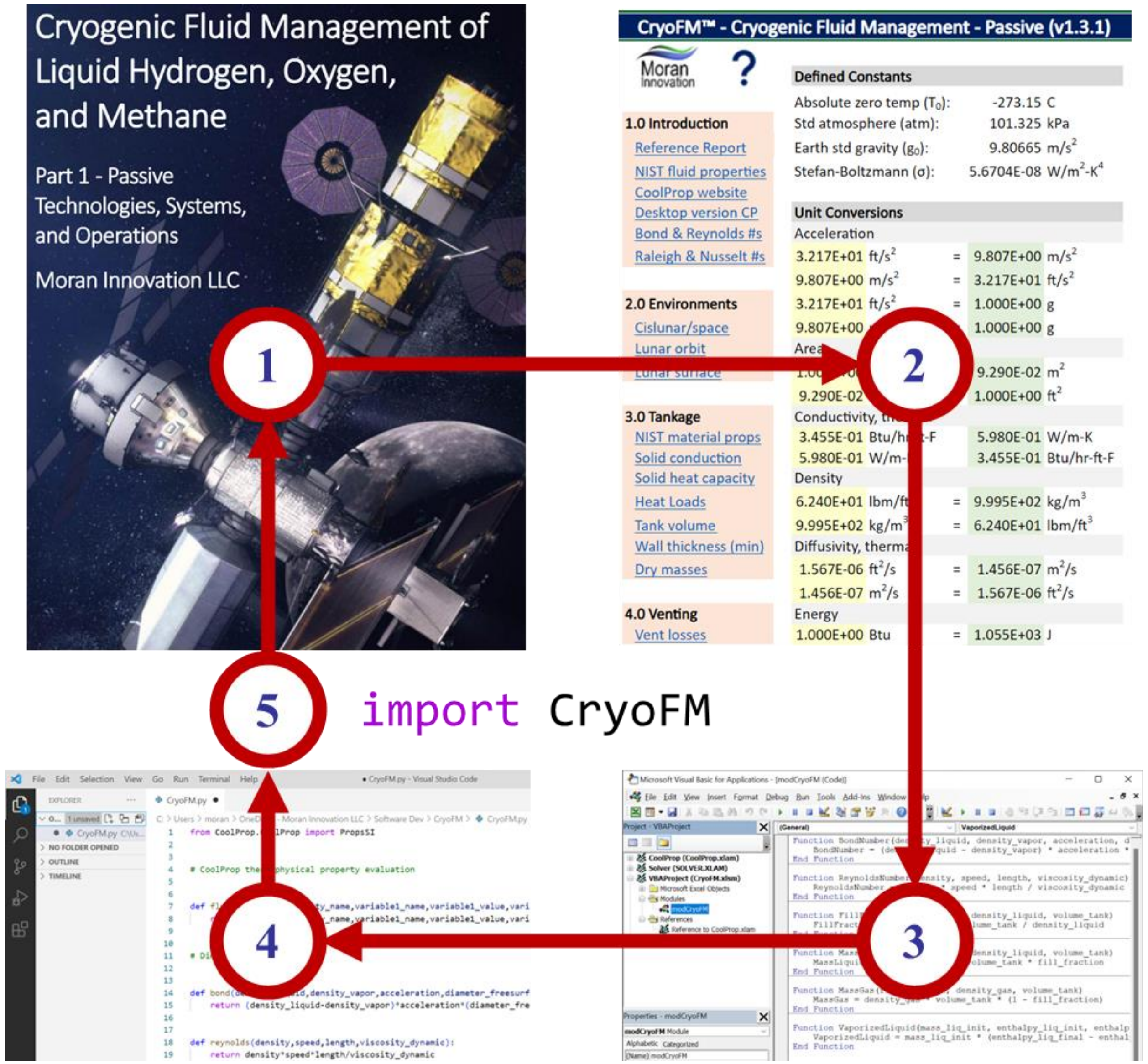
In [9]:
```
visc_dynamic = CP.PropsSI('V','T',temp,'P', pressure,fluid) # Pa-s
```

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

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

```
6.752322e+06
```

Status and Forward Plans



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

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