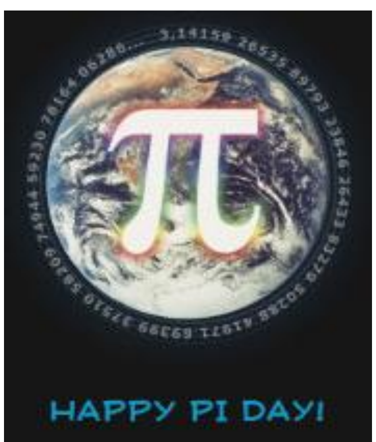
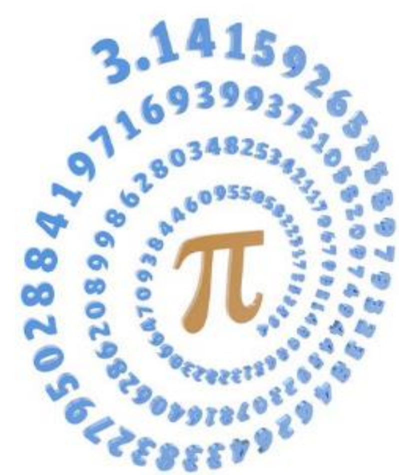
Celebrating Pi (π) Day with the American Institute of Chemical Engineers Cleveland Section

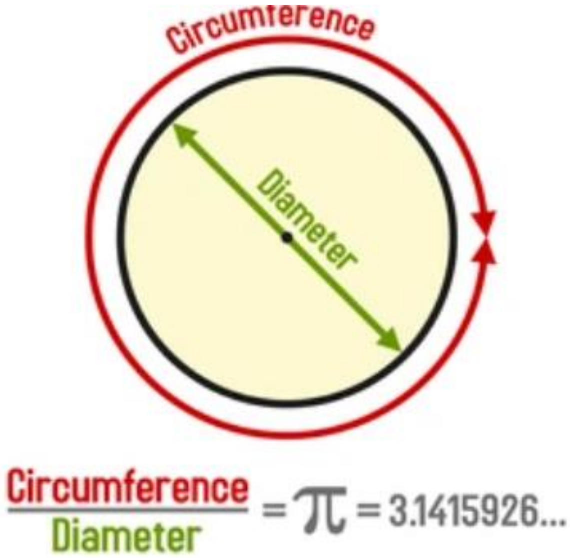
Joseph Yurko, PE, AIChE Fellow



March 14, 2022



How do Chemical Engineers use Pi?



Pi is used with Material & Energy Balances

- For Industrial Tanks and Vessels (Material Balance)
  - Pi is used to calculate the volume in a vertical tank
  - Pi is used to calculate the volume in a horizontal tank
  - Pi is used to calculate the time to fill or empty a tank
- For Industrial Pipes (Material & Energy Balances)
  - Pi is used to calculate the fluid velocity in a pipe
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- For Industrial Pumps (Material & Energy Balances)
  - Pi is used to calculate the motor horsepower to pump fluid through a pipe
  - Pi is used to calculate the carbon footprint of the pump motor horsepower

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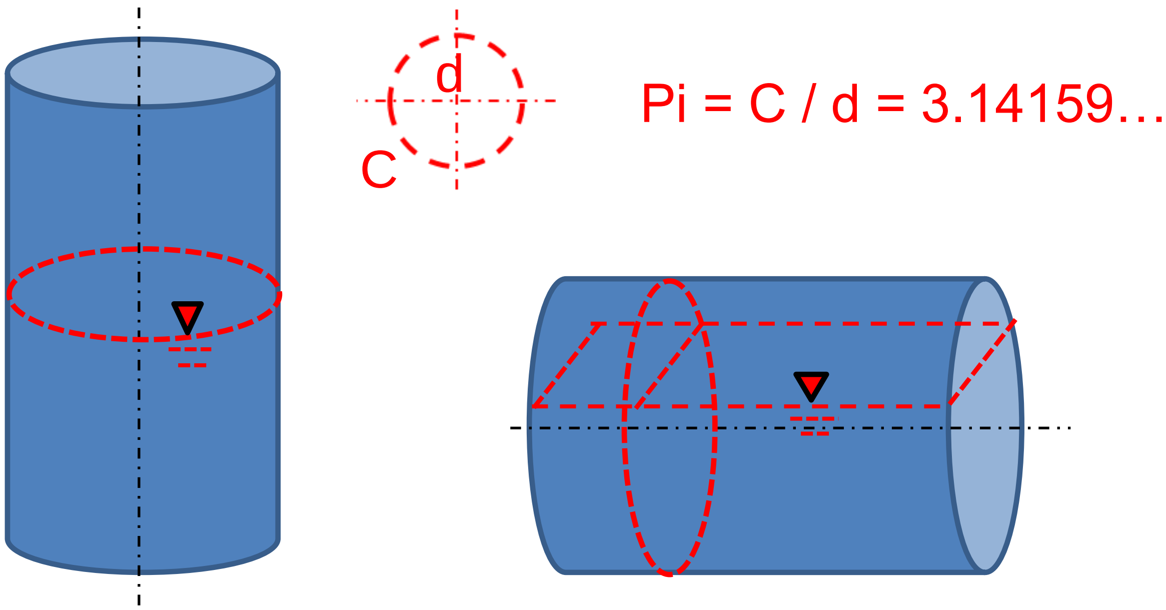
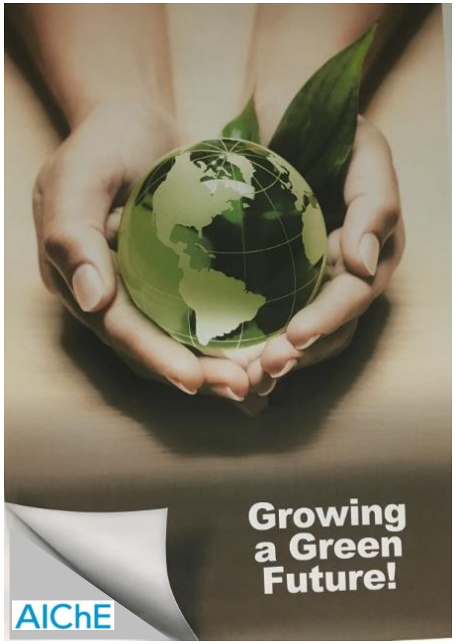
Using Pi (π) to calculate the volumes of tanks that are either vertical or horizontal.



Vertical Tank

Horizontal Tank



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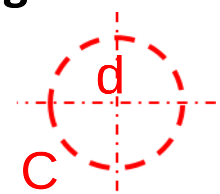
Beverage Production Facility: Where Pi is Applied

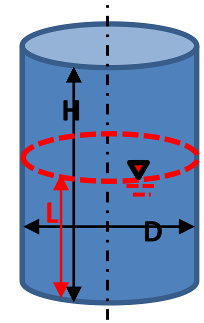
How Pi (π) is used in our Flow Calculations with Fluid Dynamics

How to calculate the volume in a vertical tank knowing:

- The tank height (H)
- The tank diameter (D)
- The liquid Level (L)



Pi = C / d = 3.14159…



Vertical Tank Elevation

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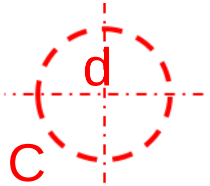
Beverage Production Facility: Where Pi is Applied

How Pi (π) is used in our Flow Calculations with Fluid Dynamics

How to calculate the volume in a vertical tank knowing:

NOTE: Pi = π = 3.1416...

Vertical Tank			Units	INPUT	Units
Tank Height (H) =	(GIVEN)		Ft	10	Ft
Tank Diameter (D) =	(GIVEN)		Ft	5	Ft
Volume (V) =	π D^2*H / 4	(FIND)	Cu Ft	196.4	Cu Ft
Level of Liquid (L) =	(GIVEN)		Ft	5	Ft
Volume Level (v) =	π D^2*H / 4	(FIND)	Cu Ft	98.2	Cu Ft
Percent Full (%) =	V / v *100	(FIND)	%	50	%
Transfer Rate (t) =	Cu Ft / Minute	(FIND)	Cu Ft / Minute	3	Cu Ft / Minute
Fill Time (T) =	Volume / Transfer Rate	(FIND)	Minutes	32.7	Minutes



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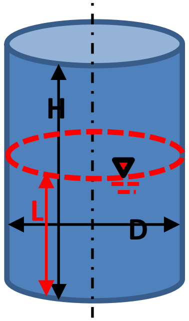

Vertical Tank Elevation

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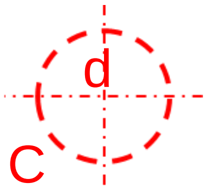
Beverage Production Facility: Where Pi is Applied

How Pi (π) is used in our Flow Calculations with Fluid Dynamics

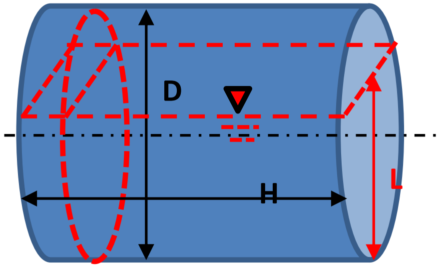


Pi = C / d = 3.14159…

How to calculate the volume in a horizontal tank knowing:

- The tank height (H)
- The tank diameter (D)
- The liquid Level (L)

Horizontal Tank Elevation



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Beverage Production Facility: Where Pi is Applied

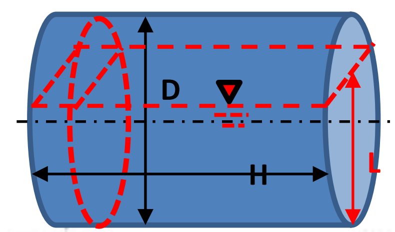
How Pi (π) is used in our Flow Calculations with Fluid Dynamics

NOTE: Pi = π = 3.1416...

<u>Determine the volume of a horizontal vessel given the diameter of the vessel and the liquid level inside the vessel</u>

<u>Solution Steps</u>	<u>Run #1</u>	<u>Run #2</u>	<u>Units</u>
Enter Inside Tank Diameter:	5	2.5	= d
Calculate Tank Radius:	2.5	1.25	=r
Calculate r2:	0.5	0.25	= r2
Feet down from Tank Top to Liquid Surface =	2	1	Ft
Depth of Liquid from surface (D) =	3	1.5	Ft
Area - A =	0.61	0.15	Sq. Ft.
Area - B =	0.61	0.15	Sq. Ft.
COS Th =	0.20	0.20	
Th =	78.46	78.46	degrees
Al =	11.54	11.54	degrees
Area - C =	11.08	2.77	Sq. Ft.
Total Area (A + B + C) =	12.30	3.08	Sq. Ft.
Length (H) =	10.00	10.00	Ft.
Liquid Volume (Cu Ft) =	123.01	30.75	Cu Ft.
Liquid Volume (Gal) =	920.22	230.05	Gal
Transfer Rate (t) = Cu Ft / Minute (FIND) Cu Ft / Minute	3	3	Cu Ft / Minute
Fill Time (T) = Volume / Transfer Rate (FIND) Minutes	41.0	10.3	Minutes

Horizontal Tank Elevation



<u>HORIZONTAL VESSEL PARTIALLY FILLED WITH LIQUID</u>

DETERMINE THE VOLUME OF THE LIQUID

FIND:
The volume in cubic feet of the Horizontal Vessel:

RH = (cross sectional flow area) / (wetted perimeter)

COS (Th) = 4 / r = (D-r) / r

(Al) = 90 - COS^(-1)(COS (Th))

AREA C = pi * d^2 /4 *[(180+(2*Al))/360]

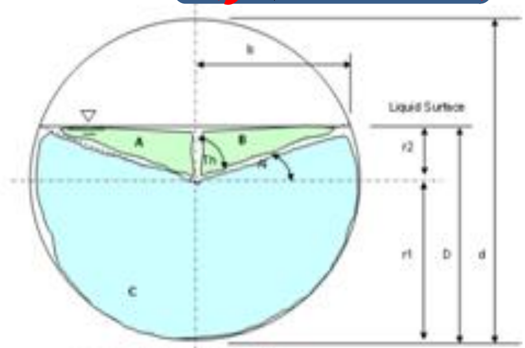
b = (r^2 - (D-r))^(0.5)

AREA A = AREA B = 0.5 * ((D-r) * b)

Total Cross Sectional Area = A + B + C

d^2 = 4 * (Total Cross Sectional Area) / pi

Multiply the total cross sectional area by the length of the vessel



<u>CROSS SECTION OF HORIZONTAL VESSEL</u>

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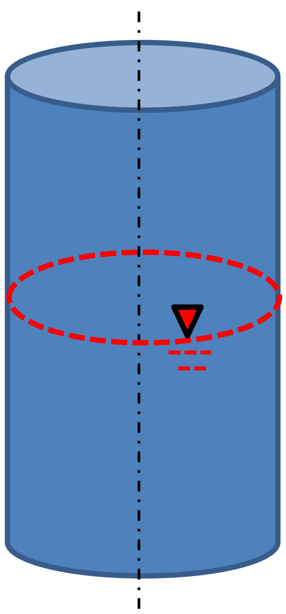
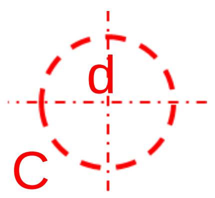
Using Pi (π) to calculate the volumes of tanks that are either vertical or horizontal.





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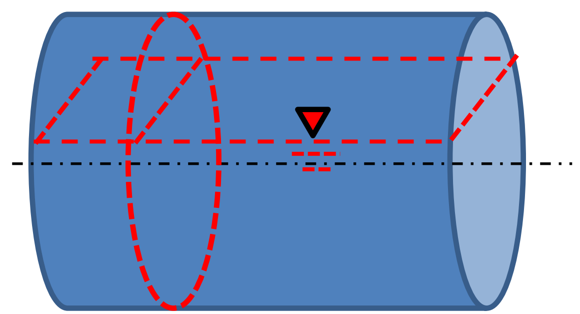

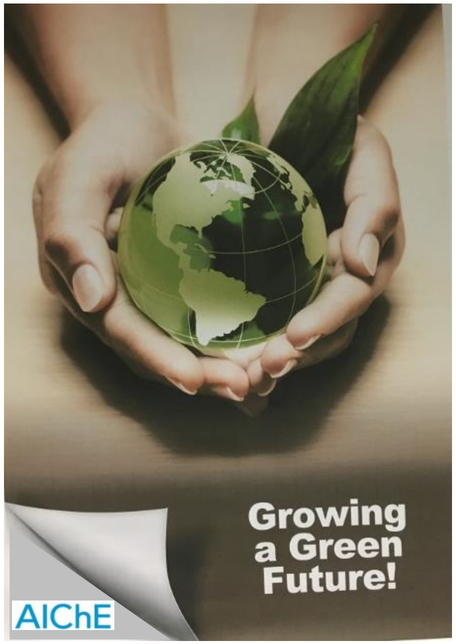

Vertical Tank

Horizontal Tank

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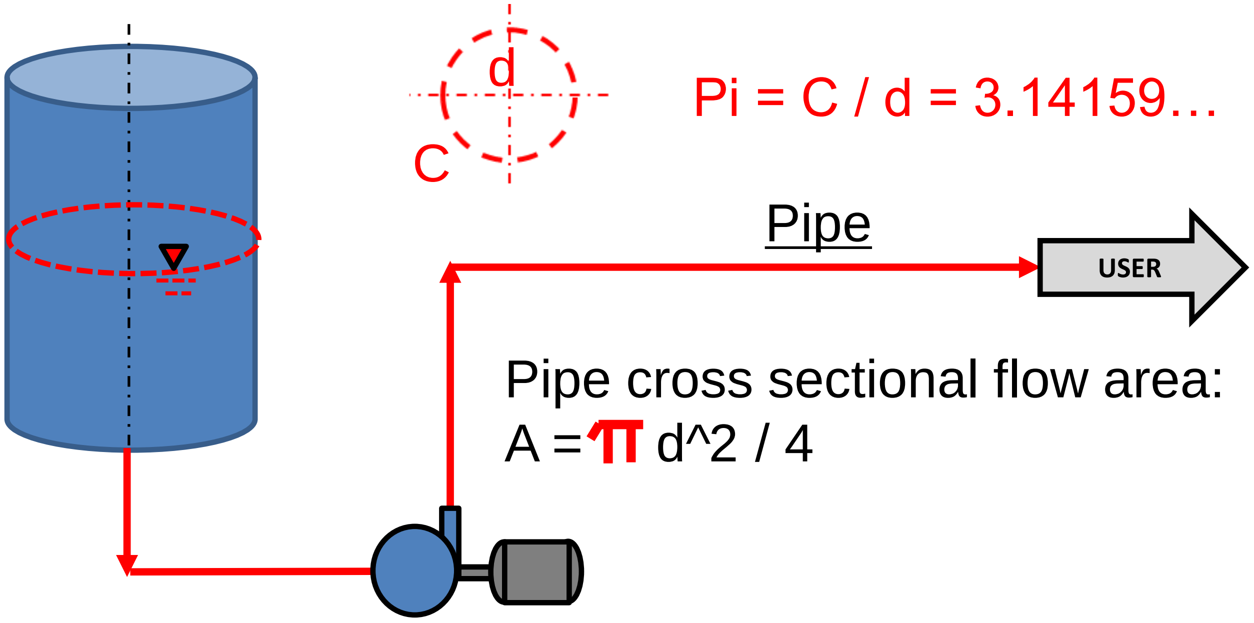
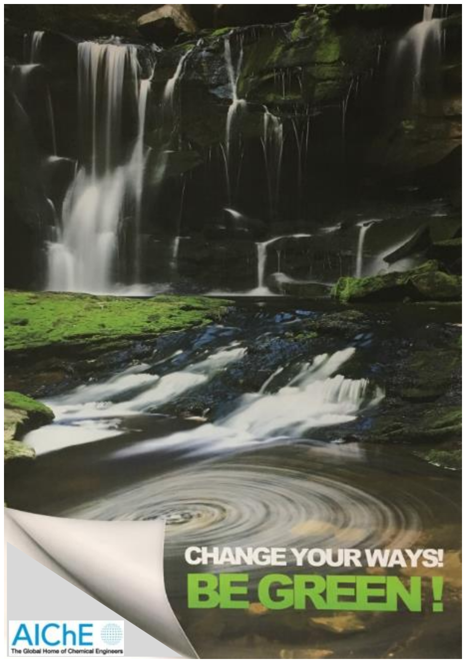
Use Pi (π) to calculate the Energy to Pump a Fluid in a Pipe. Use the Carbon Footprint of the Pumping Energy comparing different pipe sizes. This will generate the most sustainable pipe size and pump size in the system design process.



Pump & Motor

Energy to Pump Fluid in Pipe



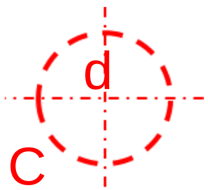
Carbon Footprint of System Pumping Energy

Pharmaceutical Production Facility: Where Pi is Applied

How Pi (π) is used in our Energy Calculations with Fluid Dynamic Pump Head

Where the fluid flow velocity inside the pipe is calculated as:

V = Ft^3 / sec / π x d^2 / 4 = Ft / sec of fluid flow velocity in the pipe



Pi = C / d = 3.14159…

Needed to calculate the optimum pump size:

- The pipe inside diameter (d, in feet)
- The pipe length (L, in feet)
- The installed pipe cost per foot ($/ft)
- The fluid and flow rate (gpm, or ft^3/sec)
- The fluid density (ro) and viscosity (cP)
- The pump cost ($, in USD) and efficiency (ep)
- The pump motor cost ($) and efficiency (em)
- The sustainable engineering Life Cycle cost of electricity per pound of Carbon Dioxide

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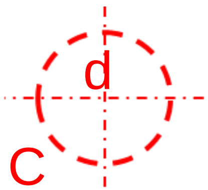
Pharmaceutical Production Facility: Where Pi is Applied

How Pi (π) is used in our Energy Calculations with Fluid Dynamic Pump Head

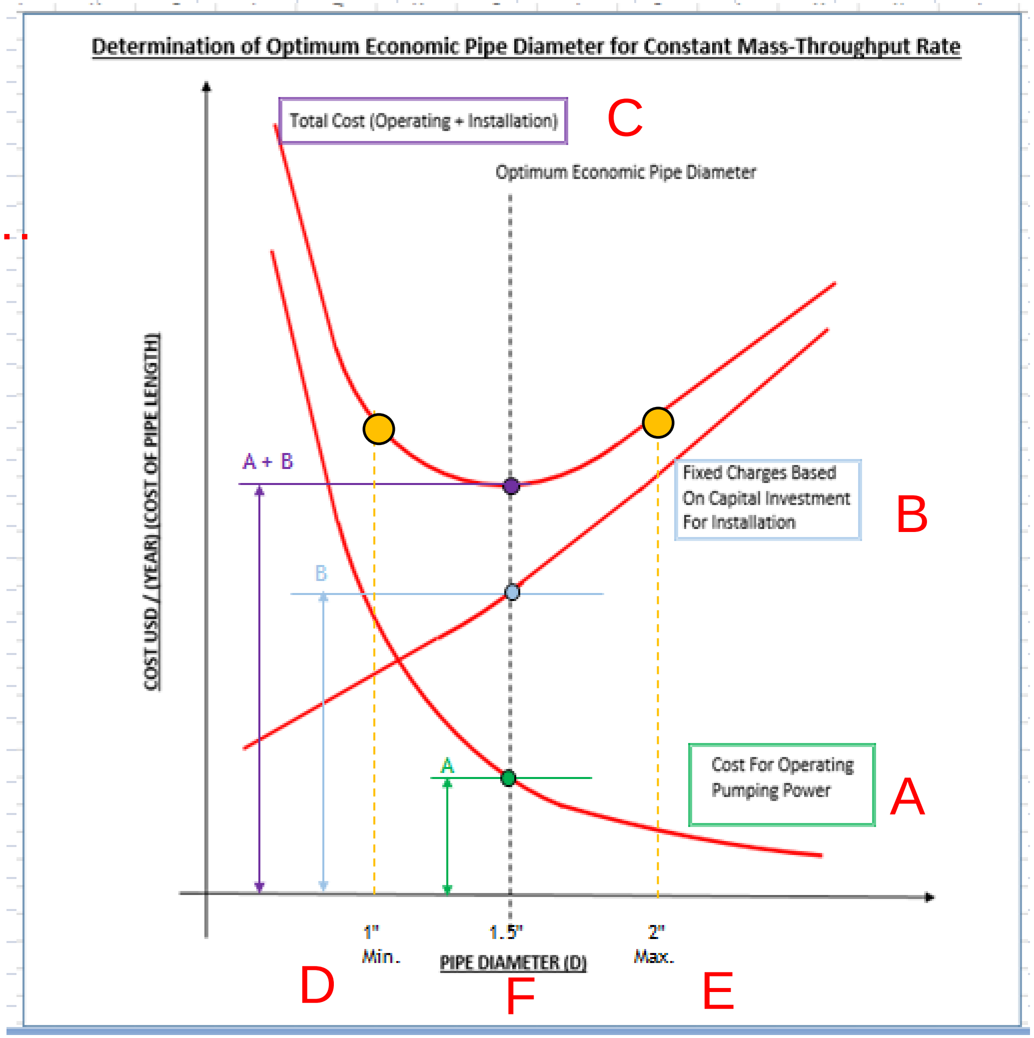
NOTE: Pi = π = 3.1416...



Pi = C / d = 3.14159…

How to calculate the Optimum Pipe Size (Min. – Max.):

- Trial & Error Technique
- Bisection Method
- Based on Flow Rate (gpm)
- First Try Minimum Dia. (1”)
- Secondly Try Maximum Dia. (2”)
- Select Value in between (1.5”)



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Pharmaceutical Production Facility: Where Pi is Applied

How Pi (π) is used in our Energy Calculations with Fluid Dynamic Pump Head

Pipe Fluid Flow Velocity			Run # 1	Run # 2	Run # 3	Run # 1	Run # 2	Run # 3	Units
Flow Rate (Q) =	(GIVEN)		30	30	30	0.0668	0.0668	0.0668	Cu Ft / Sec
Inside Pipe Diameter (d) =	(GIVEN)		1	2	1.5	0.0833	0.1667	0.1250	Ft
Pipe Installed Cost/Foot =	(GIVEN)		$15.00	$30.00	$22.50				$ / Ft
Pipe Equivalent Length =	(GIVEN)					1,000	1,000	1,000	Ft
Pipe Cost (estimated) =	(GIVEN)					$15,000	$30,000	$22,500	$
Velocity (v) =	$\frac{Q * 4}{\pi D^2}$	(FIND)				12.2	3.1	5.4	Ft / Sec
Density (ro) =	(GIVEN)					62.4	62.4	62.4	Lbs / Cu Ft
Viscosity (cP) =	(GIVEN)					1	1	1	cP
Reynolds Number(Nre)=	$\frac{Lbs}{Cu Ft}$ $\frac{CuFt * 4}{\pi D^2}$ $\frac{D}{Viscosity}$	(FIND)				9.46E+04	5.91E+03	1.87E+04	N/A
Specific Gravity (SG) =	(GIVEN)					1.00E+00	1.00E+00	1.00E+00	N/A
Friction Factor (f) =	1.8 LOG $\frac{Nre}{7}$ ^(-2)	(FIND)				0.1055	0.2101	0.1533	N/A
Pressure Drop (Ft/1,000')=	0.0311 f 1,000' Q^2 / d^5	(FIND)				2952.4	183.8	565.1	Ft/1,000
Pump Efficiency (ep)=	(GIVEN)					0.70	0.70	0.70	N/A
Pump Brake Horsepower (BHp) =	Q*Ft*SG / 3,960/ep =	(FIND)				32.0	2.0	6.1	BHp
Motor Efficiency (em) =	(GIVEN)					0.65	0.65	0.65	N/A
Pump Motor Horsepower (MHp) =	BHp / em =	(FIND)				49.2	3.1	9.4	MHp
Pump Motor Horsepower (MHp) =	BHp / em =	(TABLE)				50	5	10	MHp
Pump Motor Horsepower (MHp) =	MHp * 745.7 Watts/Hp	(FIND)				36,657	2,282	7,016	Watts
Pump Motor Cost ($ estimated) =	$ =	(TABLE)				$20,000	$2,000	$4,000	$

STANDARD PUMP MOTOR HORSEPOWER & COST (estimated) TABLE

0.25 Hp	$100	3 Hp	$1,200	25 Hp	$10,000	100 Hp	$40,000
0.5 Hp	$200	5 Hp	$2,000	30 Hp	$12,000	125 Hp	$50,000
0.75 Hp	$300	7.5 Hp	$3,000	40 Hp	$16,000	150 Hp	$60,000
1 Hp	$400	10 Hp	$4,000	50 Hp	$20,000	200 Hp	$80,000
1.5 Hp	$600	15 Hp	$6,000	60 Hp	$24,000	250 Hp	$100,000
2 Hp	$800	20 Hp	$8,000	75 Hp	$30,000	300 Hp	$120,000

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Pharmaceutical Production Facility: Where Pi is Applied

How Pi (π) is used in our Energy Calculations to generate a Carbon Footprint that will be used to evaluate the system sizing and sustainable design

Sustainable Engineering, Principles and Practices, Dr. Bakshi, Cambridge University Press, 2019

Chapter 9, Inventory Analysis

Table 9.2, Typical Life Cycle Inventory Data from Input-Output Models

Reference: Y. Yang, W.W. Ingwersen, T.R. Hawkins, M. Srocka, and D.E. Meyer;
USEEIO: A New and Transparent United States Environmentally Extended Input-Output model, *Journal of Cleaner Production*, 158: 308-318, 2017

Flow	Units	Reference	Electricity
CO_2	kg / $	221100	6.27E+00

HIGH Run # 1 INPUT OUTPUT	LOW Run # 2 INPUT OUTPUT	MIDPOINT Run # 3 INPUT OUTPUT	
36,657	2,282	7,016	Watts
1	1	1	Hours
36,657	2,282	7,016	Wh
36.7	2.3	7.0	kWh

The Bedford Industrial Cost of Electricity is $0.07 kWh

Determine the Life Cycle of CO_2 emissions for this system based on an Input-Output model

IO Model Life Cycle CO_2 Emissions =

Run # 1 = 6.27E+00 kg/\$ ÷ \$0.07/kWh × 36.7 kWh = 16.1 kg CO_2 = 35.4 Lbs CO_2

Run # 2 = 6.27E+00 kg/\$ ÷ \$0.07/kWh × 2.3 kWh = 1.0 kg CO_2 = 2.2 Lbs CO_2

Run # 3 = 6.27E+00 kg/\$ ÷ \$0.07/kWh × 7.0 kWh = 3.1 kg CO_2 = 6.8 Lbs CO_2

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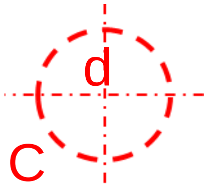

$$Pi = C / d = 3.14159\ldots$$

			Run # 1	Run # 2	Run # 3	
			1" Dia. Min.	2" Dia. Max.	1.5" Dia.	
System Installed & Operating Cost =	$ =	(FIND)	$37,566	$32,160	$26,991	$
System Carbon Footprint (CFP) =	Lbs CO2 / 1,000 Hr =	(FIND)	35	2	7	CFP
Most Sustainable (OPTIMUM) =		(FIND)	HighCO2	High $	Yes, CO2+$	

Using Pi (π) we found our Energy Calculations to generate :

1. Optimum Pipe Diameter of 1.5”
2. Pump Motor Size of 10 Hp
3. Carbon Footprint of 7 Lbs of CO2 per 1,000 hours of running time.

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Use Pi (π) to calculate the Energy to Pump a Fluid in a Pipe. Use the Carbon Footprint of the Pumping Energy comparing different pipe sizes. This will generate the most sustainable pipe size and pump size in the system design process.

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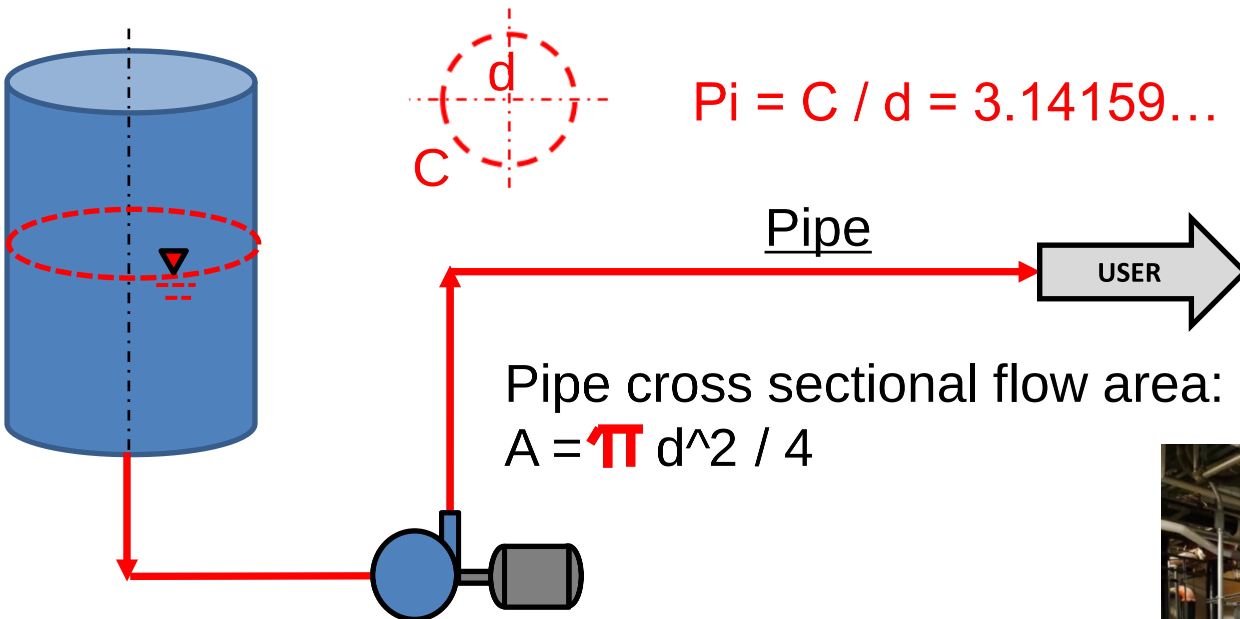

$$Pi = C / d = 3.14159\ldots$$

Pipe cross sectional flow area:

$$A = \pi d^2 / 4$$

Pump & Motor

Energy to Pump Fluid in Pipe

CWRU Capstone
Xellia Senior Project
2020 Spring Semester
Carbon Footprint of
System Pumping Energy

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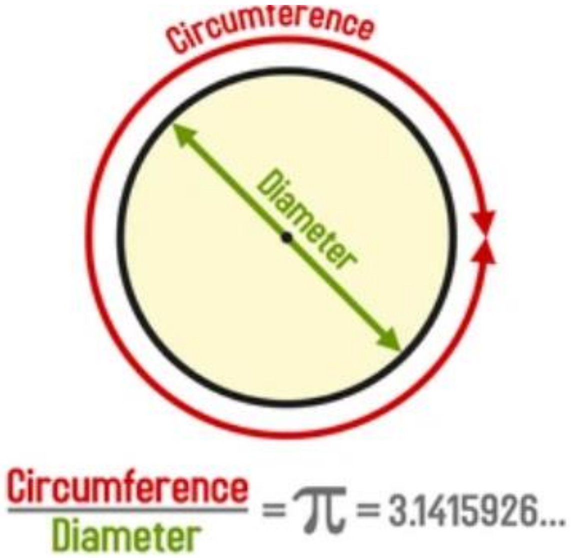
How do Chemical Engineers use Pi?



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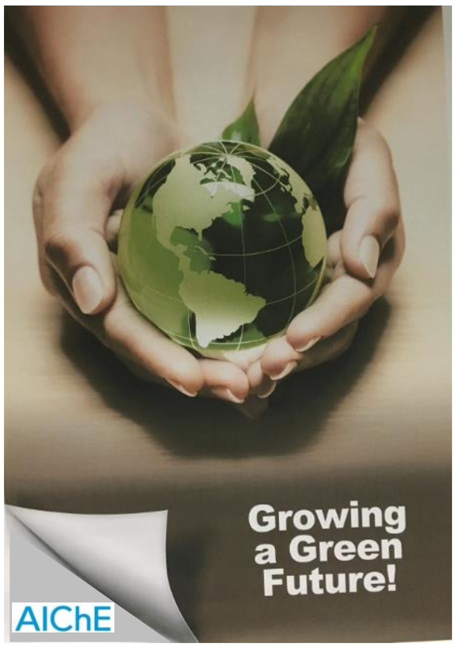
Industrial Production Facility: Where Pi is Applied



References: