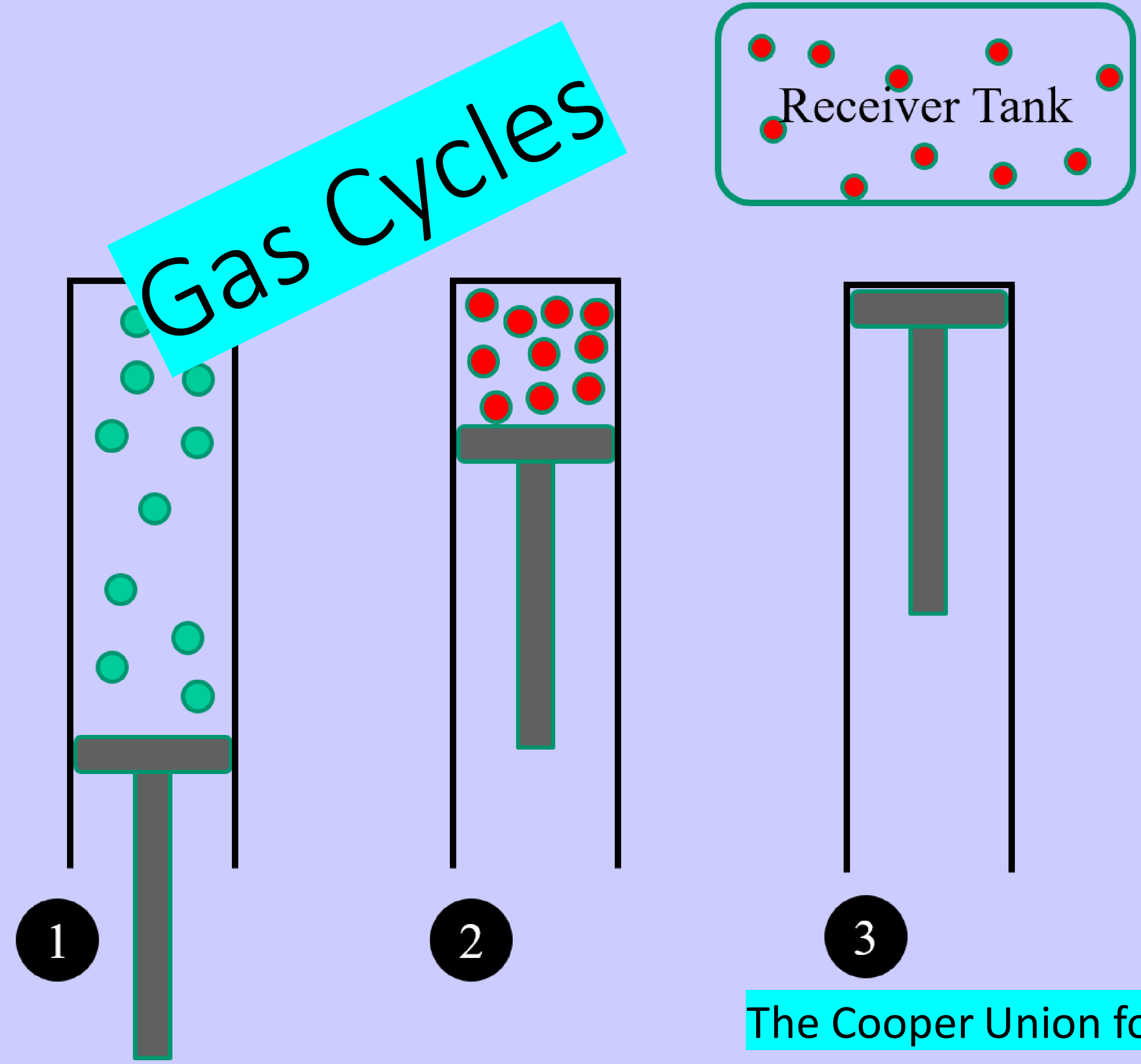
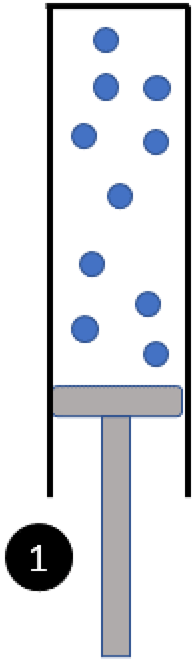
Gas Cycles





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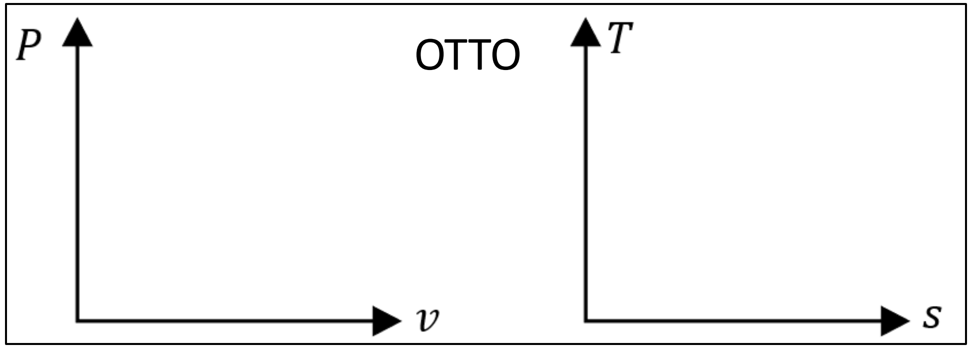
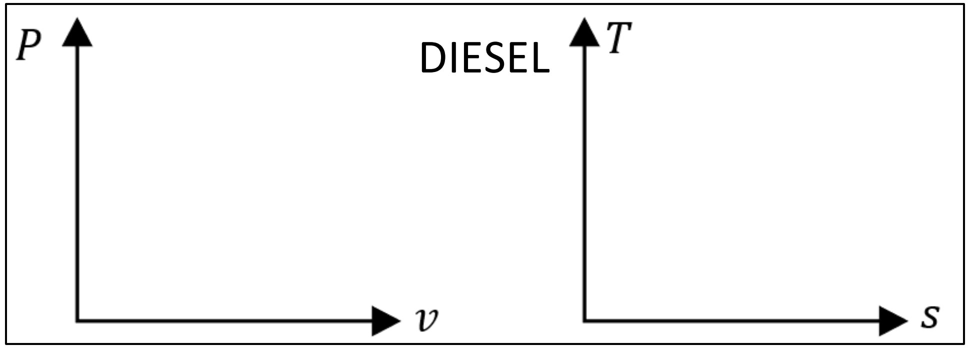
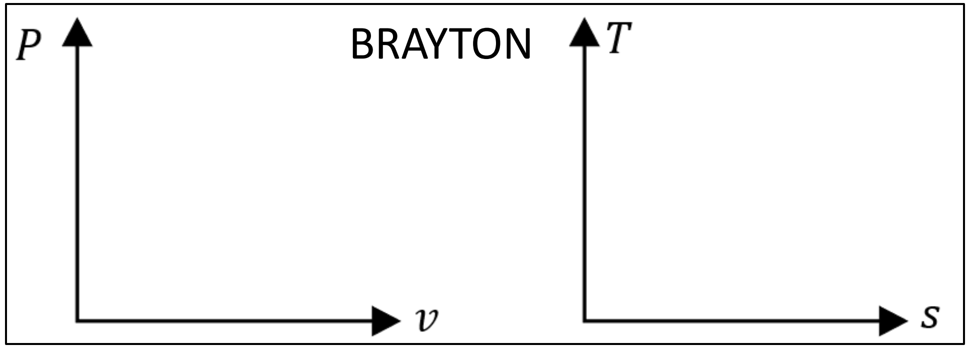
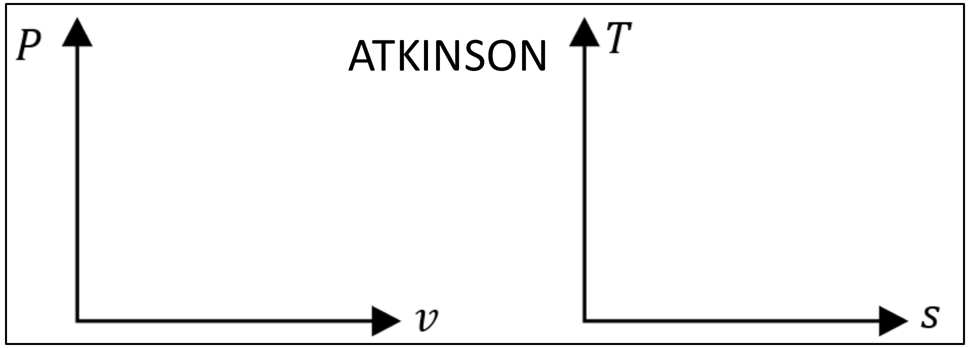
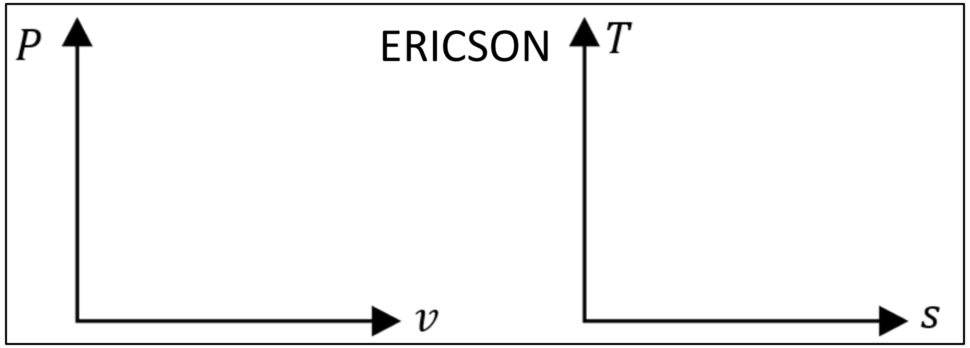
Gas Power Cycles

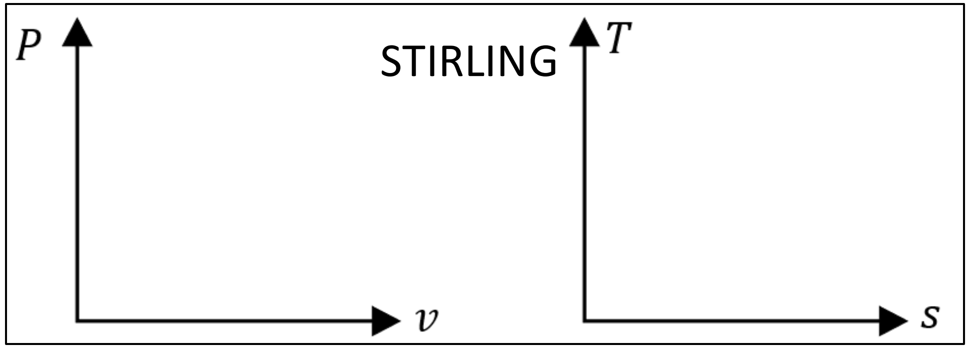












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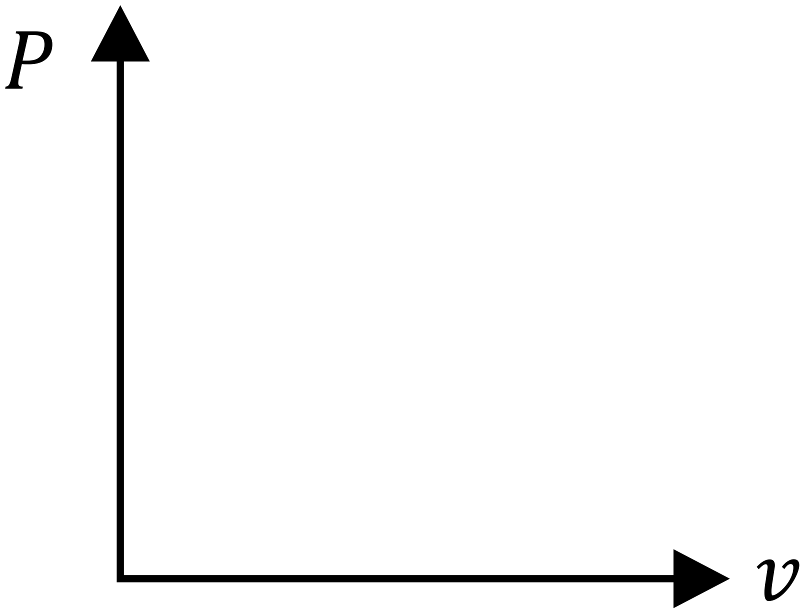
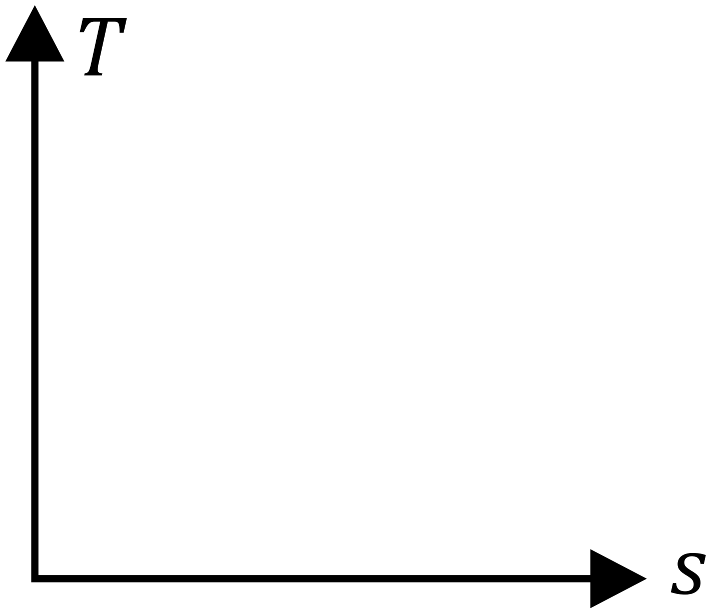
Process Type (constant property), heat exchange

Gas Cycle	***Application***	***1-2***	***2-3***	***3-4***	***4-1***
Otto	SI engine	S	V, q_{in}	S	V, q_{out}
Diesel	Diesel	S	P, q_{in}	S	V, q_{out}
Brayton	Gas Turbine	S	P, q_{in}	S	P, q_{out}
Atkinson	Turbocharge SI	S	V, q_{in}	S	P, q_{out}
Ericson	Gas Turbine +	T_C, q_{out}	P	T_H, q_{in}	P
Stirling	Toys + Future?	T_C, q_{out}	V	T_H, q_{in}	V
Carnot	THEORY	T_C, q_{out}	S	T_H, q_{in}	S





Comparison of
Otto and Diesel Cycles

https://www.youtube.com/watch?v=Pu7g3uIG6Zo

https://www.youtube.com/watch?v=s2WGFELXPNg

Similarities Between Cycles

- Reciprocating Engine (i.e. piston/cylinder)
- 4 Strokes of piston (Compression, Expansion/power, Exhaust, Intake)
- Internal combustion (fuel burns in air)
- Exhaust gases are hot, with properties close to that of air

Practical Differences between Cycles

Otto Cycle (Spark Ignition, SI)

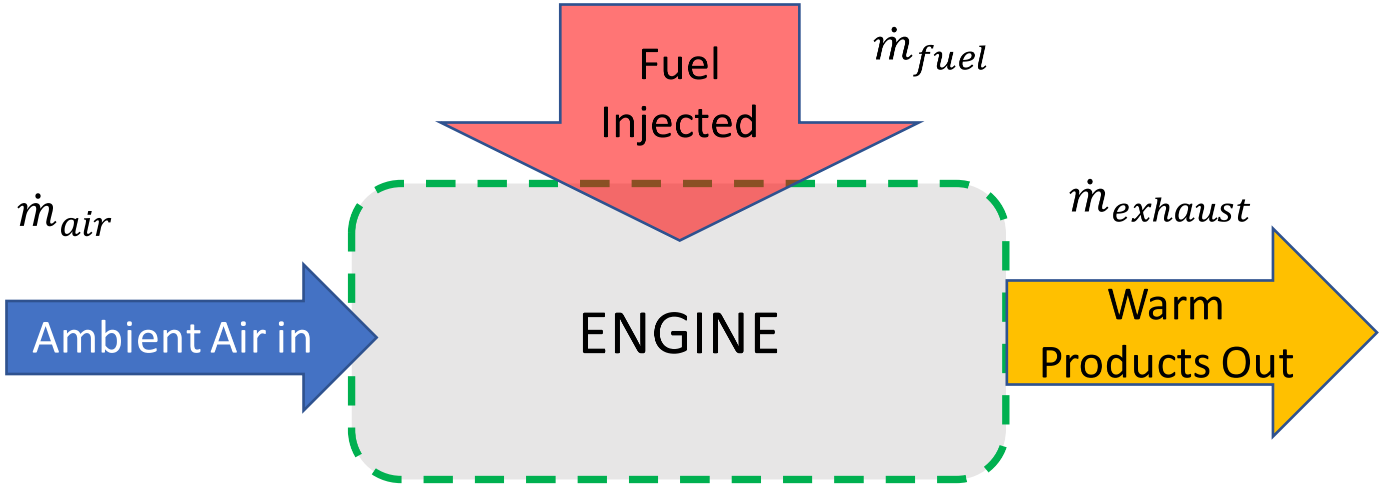
- Fuel mixed with air PRIOR to induction into cylinder. A fuel/air mixture is compressed (premixed flame to follow)
- Volume Compression Ratio limited to ~10 by the Chemical nature (premature ignition of fuel/air mixture).
- Faster combustion, limited by premixed flame propagation physics.
- Fuel/Air Ratio must be near stoichiometric (for proper flame propagation).
- Power output varied by THROTTLING (introducing entropy generation)

Diesel Cycle (Compression Ignition, CI)

- Fuel is injected directly into cylinder AFTER air is compressed (Diffusion flame to follow)
- Volume Compression Ratio limited to ~20 by mechanical limits.
- Combustion is slower, limited by mixing and diffusion rates as fuel is injected.
- Fuel/Air ratio over-all lean to limit emissions.
- Power output varied by changing amount of fuel injected. NO THROTTLE PLATE

Engine as Steady State Open System

The engine output appears steady while each cylinder undergoes its series of processes.



Volumetric Efficiency:

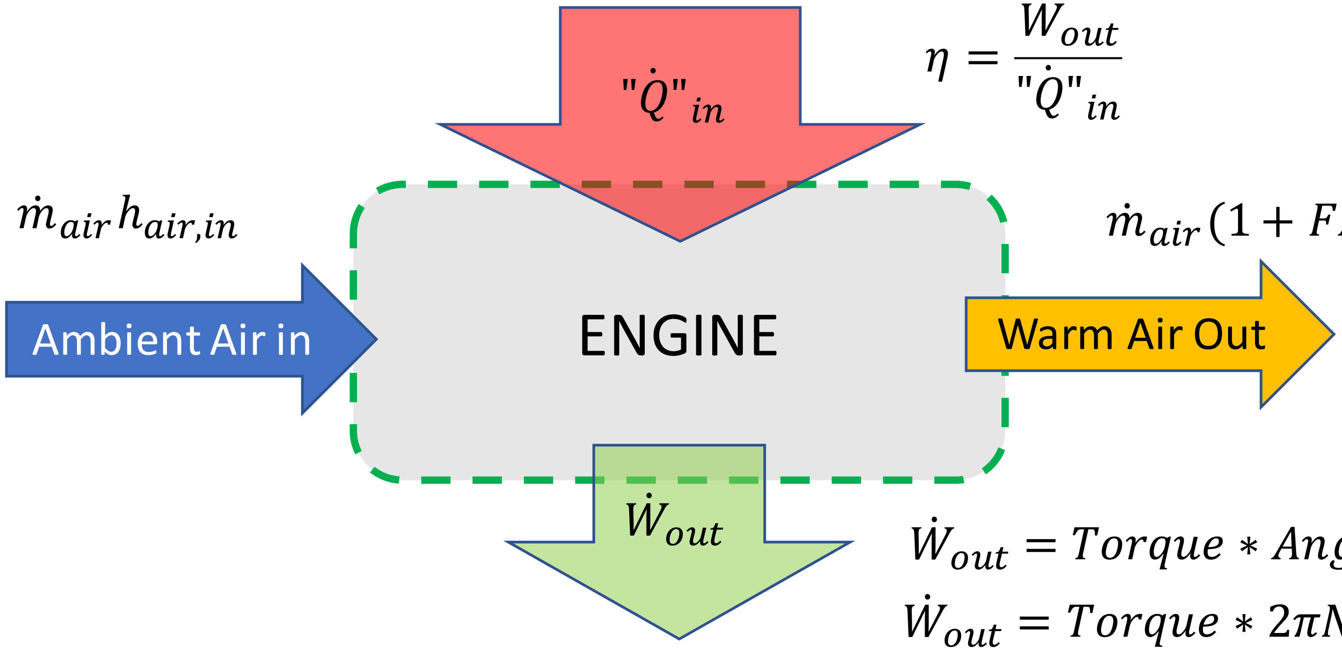
(Intake Flow effects, i.e. fluid mechanics)

$$\eta_v = \frac{Mass\ Inducted}{Ideal\ Mass\ Inducted}$$

$$\dot{m}_{air} = n_{cylinder} * \underbrace{\left(\frac{Mass\ inducted}{cylinder * cycle}\right)}_{\eta_v \rho_1 V_d} * \left(\frac{cycle}{2\ rev}\right) * \left(N\frac{rev}{min}\right) * \left|\frac{min}{60\ sec}\right|$$

$$\dot{m}_{exhaust} = \dot{m}_{air} + \dot{m}_{fuel} = \dot{m}_{air}(1 + \underbrace{FAR_{mass}}_{\text{Fuel to Air Mass Ratio} \sim 0.05 \text{ or less typically}})$$

Engine as Steady State Open System



$\dot{m}_{air} h_{air,in}$

$\dot{m}_{air}(1 + FAR_{mass}) h_{products}$

$$\eta = \frac{\dot{W}_{out}}{"\dot{Q}"_{in}}$$

$$\dot{W}_{out} = Torque * Angular\ Speed = \tau\omega$$

$$\dot{W}_{out} = Torque * 2\pi N$$

Work of cycle per unit mass of fuel/air inducted

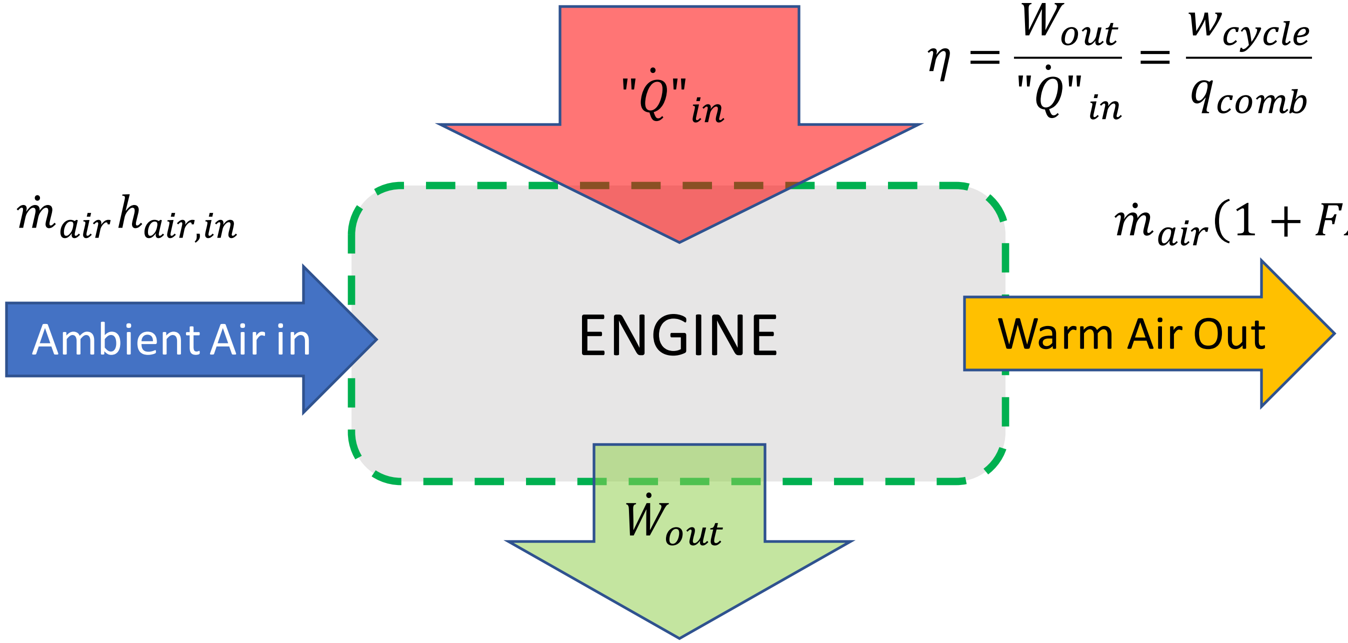
$$\dot{W}_{out} = n_{cylinder} * \left(\frac{mass\ inducted}{cylinder * cycle}\right) * \left(\frac{Work}{mass\ inducted}\right) * \left(\frac{cycle}{2\ rev}\right) * \left(N\frac{rev}{min}\right) * \left|\frac{min}{60\ sec}\right| = \dot{m}_{air} w_{cycle}$$

$$"\dot{Q}"_{in} = n_{cylinder} * \left(\frac{mass\ inducted}{cylinder * cycle}\right) * \left(\frac{Chemical\ Energy}{mass\ inducted}\right) * \left(\frac{cycle}{2\ rev}\right) * \left(N\frac{rev}{min}\right) * \left|\frac{min}{60\ sec}\right| = \dot{m}_{air} q_{comb}$$

Chemical energy released per unit mass of fuel/air mixture inducted

Engine as Steady State Open System

$$\eta = \frac{\dot{W}_{out}}{"\dot{Q}"_{in}} = \frac{w_{cycle}}{q_{comb}}$$



NOTE: this stream of hot air can be used to drive either

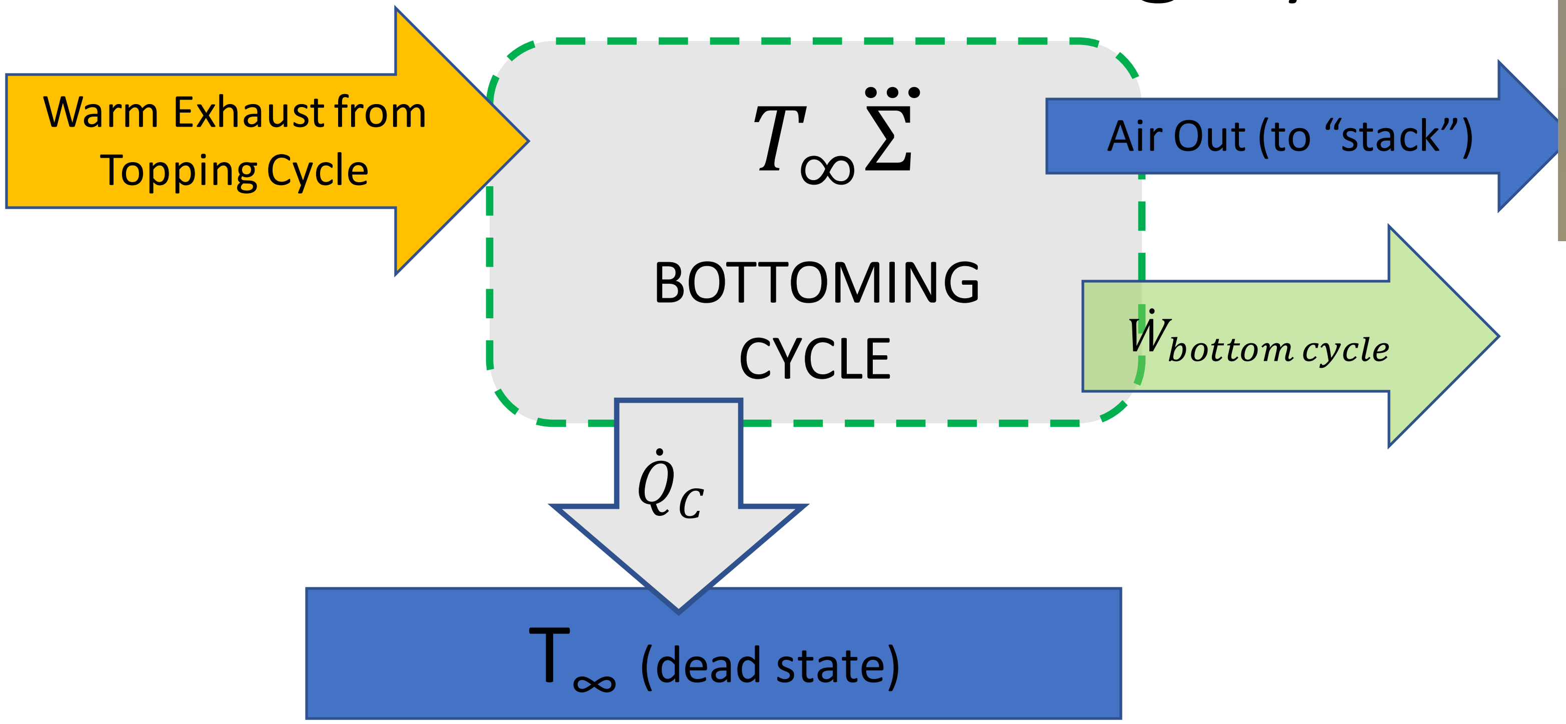
1. a RANKINE bottoming cycle (making a Combined Cycle)
2. A space heating source (making it Cogeneration)

$$\dot{m}_{air} h_{air,in} + "\dot{Q}"_{in} = \dot{m}_{air}(1 + FAR)h_{products} + \dot{W}_{out}$$

$$\dot{m}_{air} c_p (T_{exit} - T_\infty) \approx \dot{m}_{air}(q_{comb} - w_{cycle})$$

$$T_{exit} = T_\infty + \frac{q_{comb} - w_{cycle}}{c_p} = T_\infty + \frac{q_{comb}}{c_p}(1 - \eta)$$

Potential of Bottoming Cycle



Energy: $\dot{m}_{exh} h_{exh} = \dot{m}_{exh} h_{stack} + \dot{Q}_C + \dot{W}_{bottom}$

Entropy: $\dot{m}_{exh} s_{exh} + \ddot{\Sigma} = \dot{m}_{exh} s_{stack} + \dfrac{\dot{Q}_C}{T_\infty}$

Combine (by eliminating Q_C)

$$\boxed{\dot{W}_{bottom} = \dot{m}_{exh}\left[(h_{exh} - h_{stack}) - T_\infty(s_{exh} - s_{stack})\right] - \overbrace{T_\infty \ddot{\Sigma}}^{\text{Exergy destruction (i.e. energy “dissipation” due to irreversibilities)}}}$$

Gas Exchange in Ideal Throttled Otto Cycle

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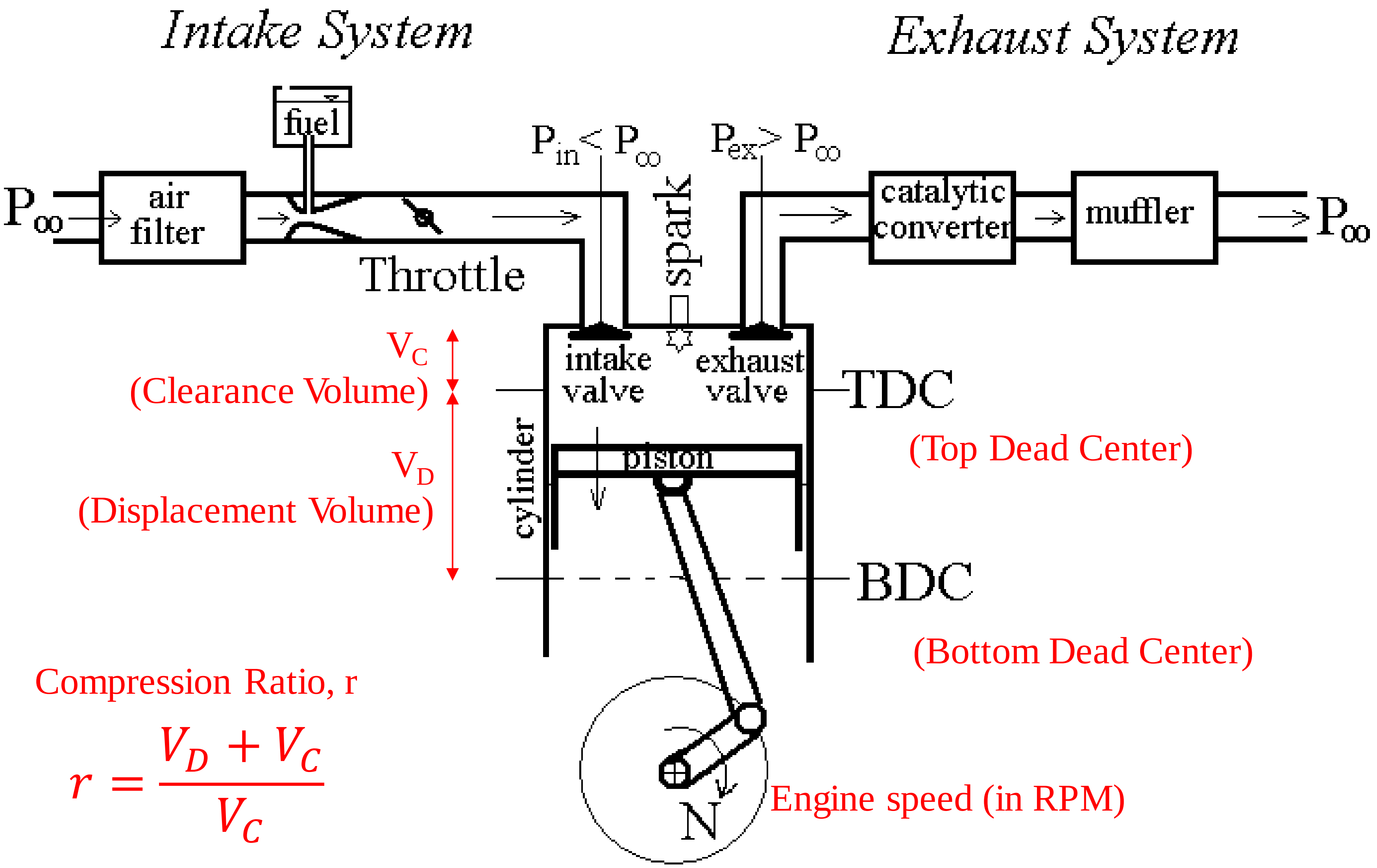


Compression Ratio, r

$$r = \frac{V_D + V_C}{V_C}$$

Process 1-2: Compression Stroke

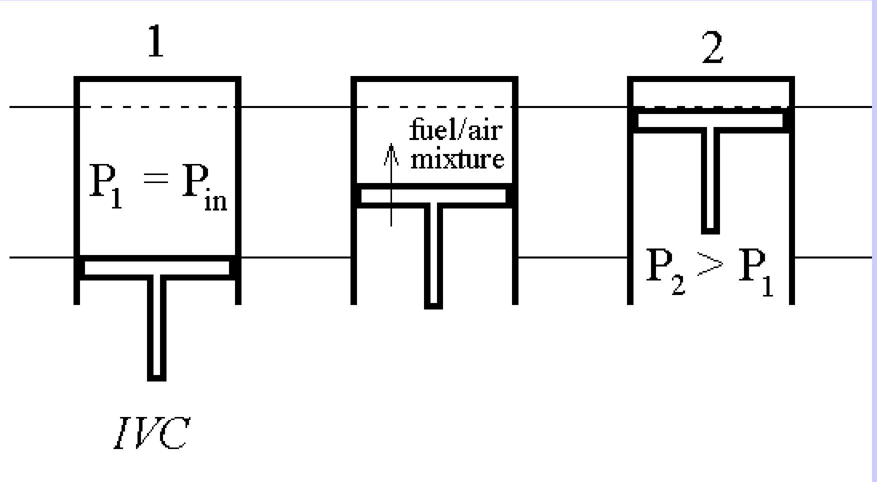
- Intake Valve Closes (IVC), trapping air/fuel mixture at P_{in} at BDC

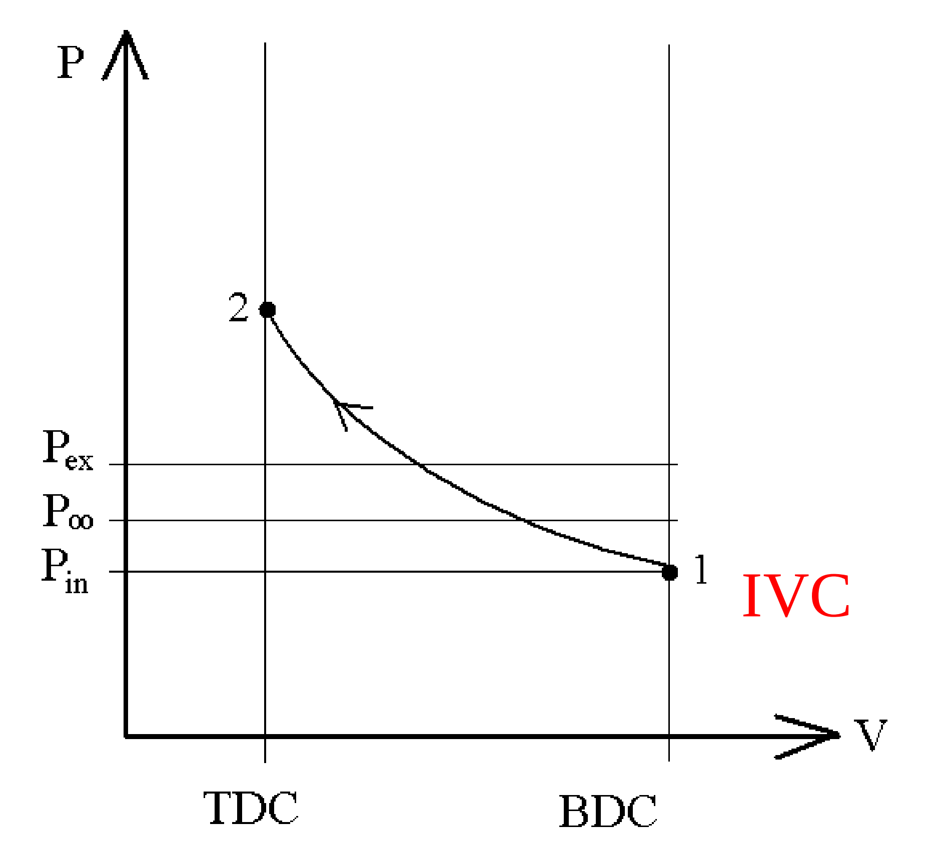
- T_1 is close to T_{in}, but not equal, because fresh charge has mixed with “residual gases”

- $M_1 = M_2 = (P_1 V_1)/(RT_1)$ can be approximated to start, but is not known precisely (T_1=?).

- Process modeled as isentropic compression in ideal cycle.

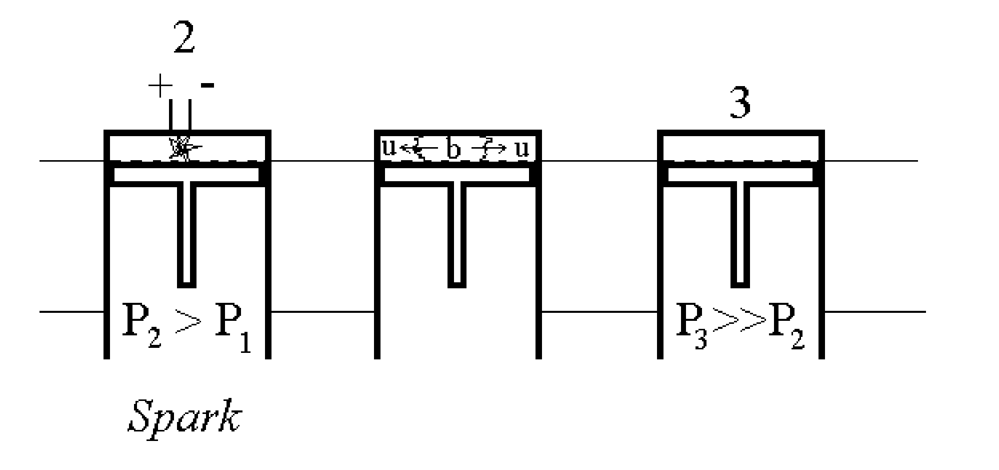
- In real cycle, there can be heat loss and friction, and the intake valve closes a little late.

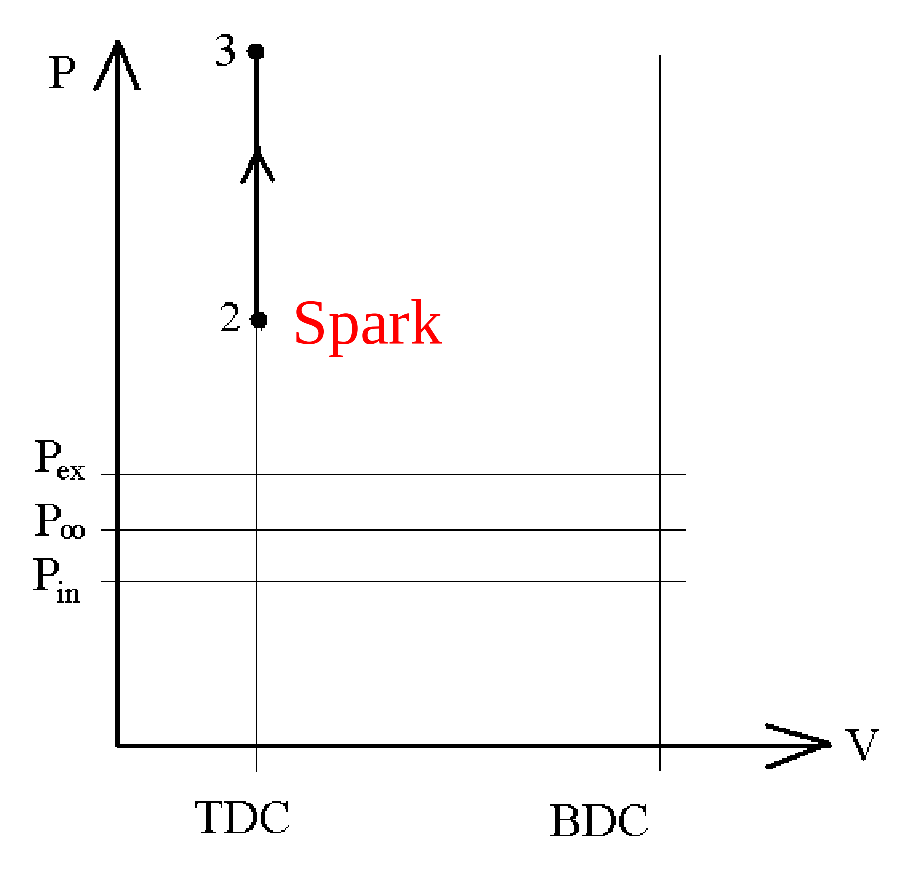




Process 2-3: Combustion

- Spark ignites fuel/air mixture.
- Premixed flame propagates into unburned gases (u) leaving burned gases (b) behind.
- Chemical energy converted to thermal energy.
- Process modeled as instantaneous constant volume heat addition in ideal cycle.
- In real cycle, combustion takes time, so spark is timed early and there is heat loss to the walls.



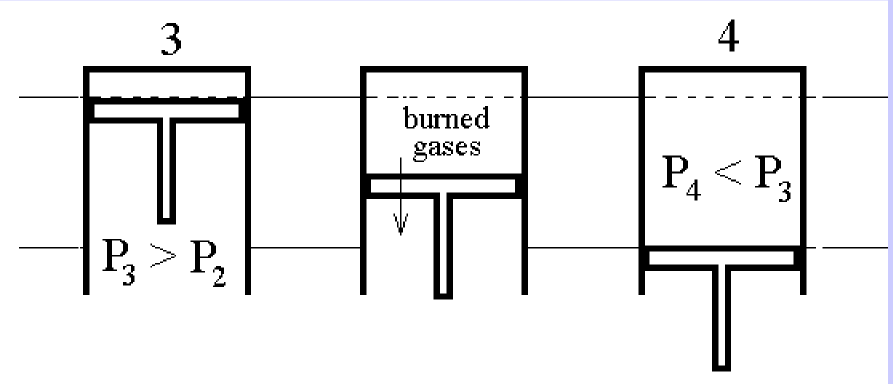


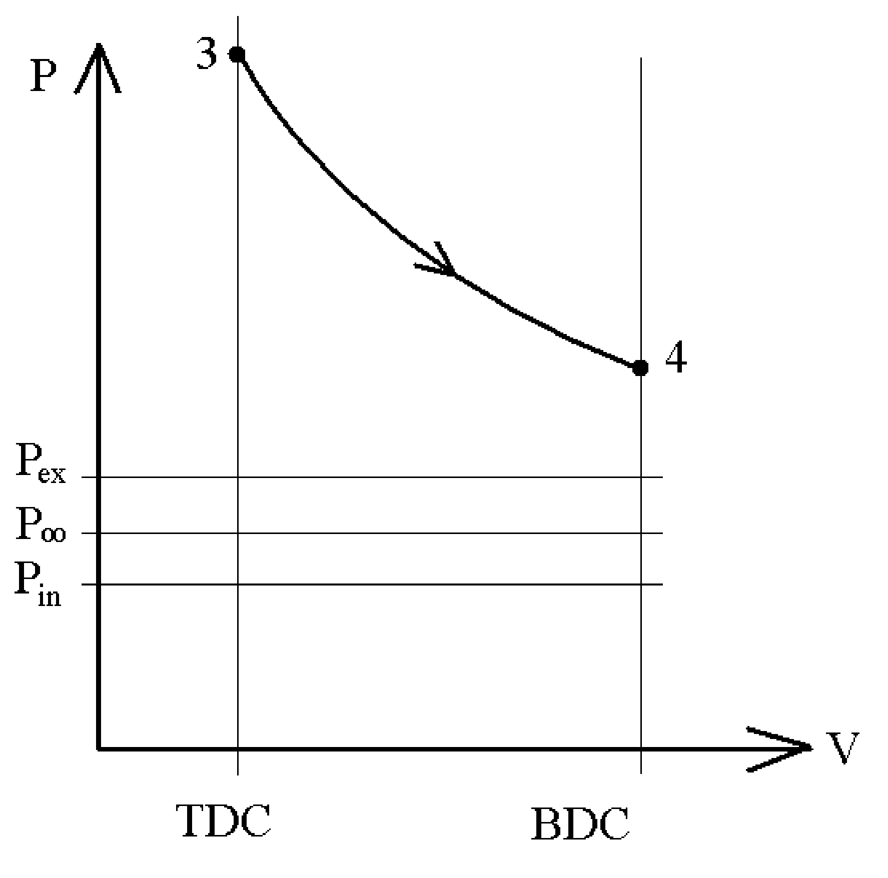
Process 3-4: Power Stroke

• Process modeled as isentropic expansion in ideal cycle.

• Work output exceeds work input of compression stroke

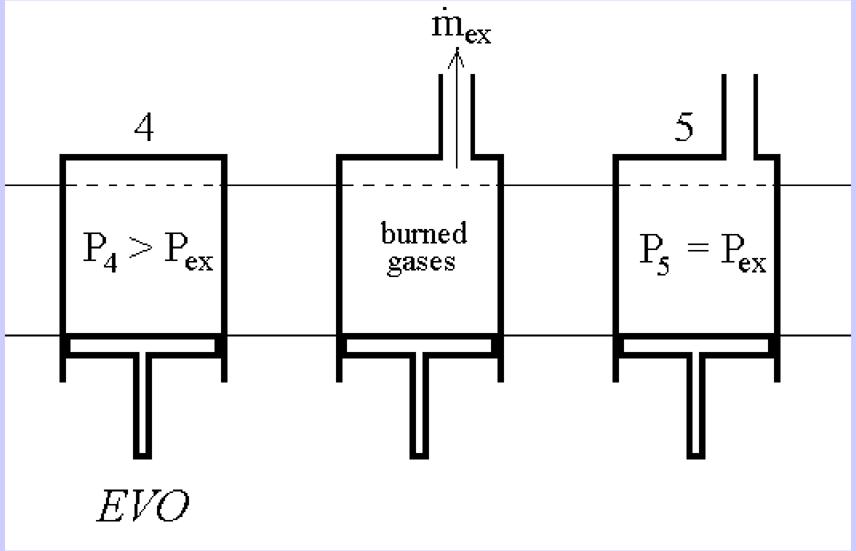
• In real cycle, exhaust valve opens early to begin "blowdown" and there is heat loss to the walls.

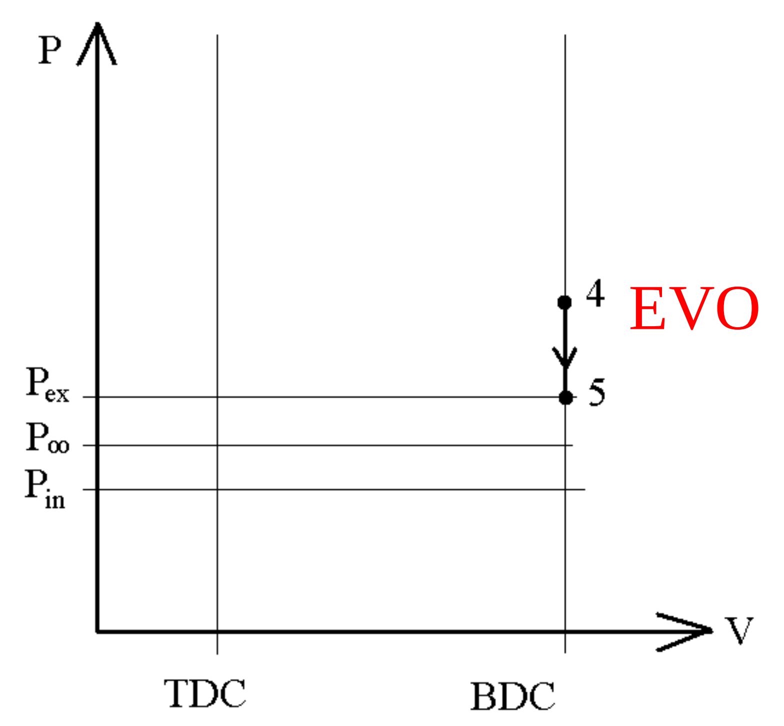




Process 4-5: Blowdown

- Exhaust valve opens (EVO) at end of power stroke, exposing still high pressure gases to exhaust manifold.
- Gases flow until pressure equilibrates with exhaust manifold (@ P_{ex}).
- Process modeled as adiabatic venting process in ideal cycle.
- In real cycle, exhaust valve opens early and blowdown is not complete before exhaust stroke starts.
- There is heat loss to the walls.





Process 5-6:
Exhaust Stroke

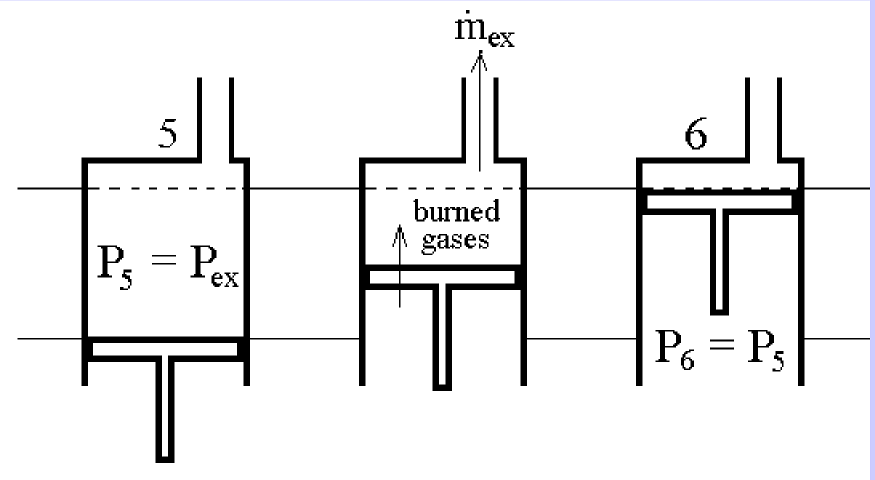
• Piston advances with exhaust valve open.

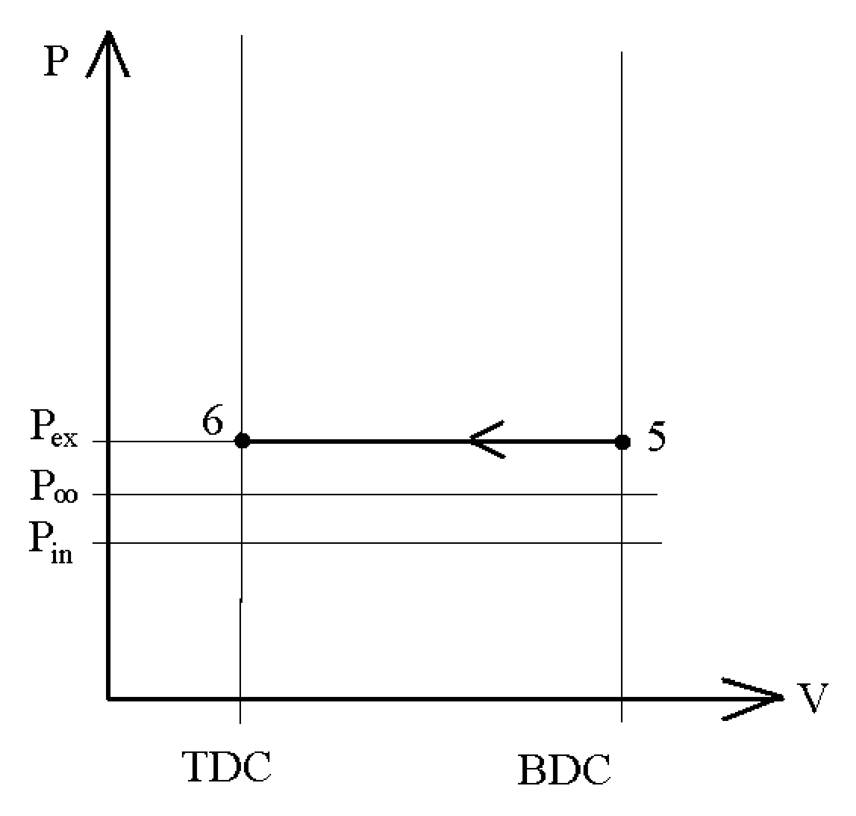
• Pressure drop across valve neglected in ideal cycle (cylinder pressure equals exhaust manifold pressure).

• Exhaust manifold pressure greater than ambient due to drops across catalytic converter, muffler and tailpipe.

• Work input required.

• In real cycle, there is a pressure drop across the valve, making the cylinder pressure greater than exhaust manifold pressure.





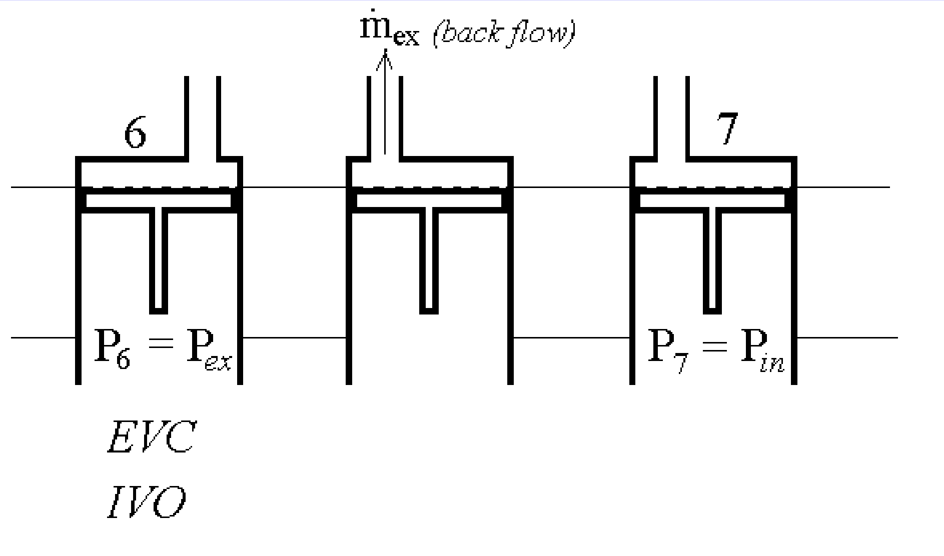
Process 6-7: Valve Overlap

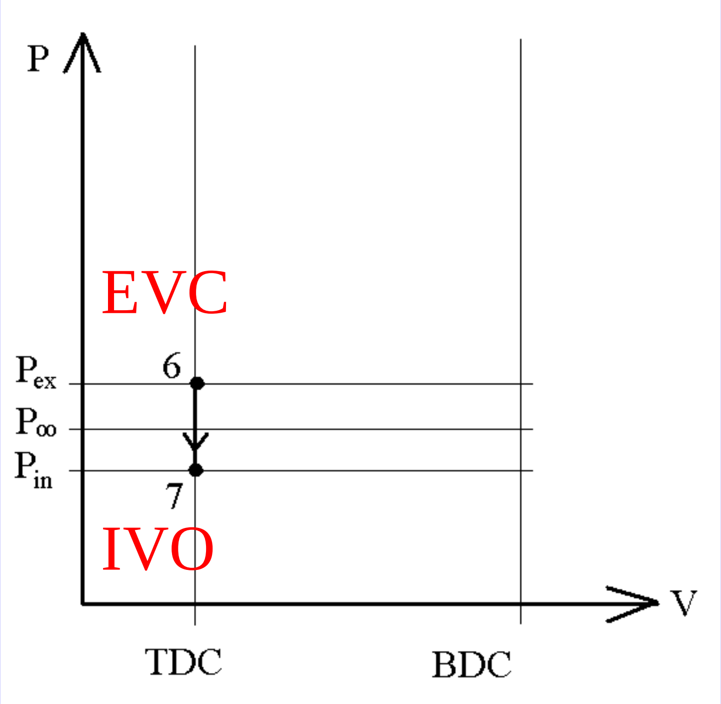
• Exhaust valve closes (EVC) as intake valve opens (IVO).

• Since intake manifold is below atmospheric and exhaust manifold is above, there is back flow into the intake manifold.

• In ideal cycle, backflow stops when cylinder pressure equals intake manifold.

• In real cycle, IVO is early, and EVC is late.





Process 7-1: Intake Stroke

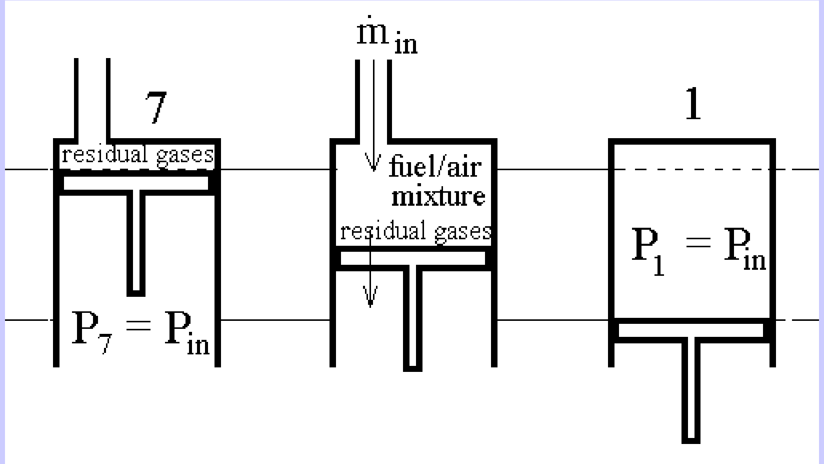
• Piston withdraws with intake valve open.

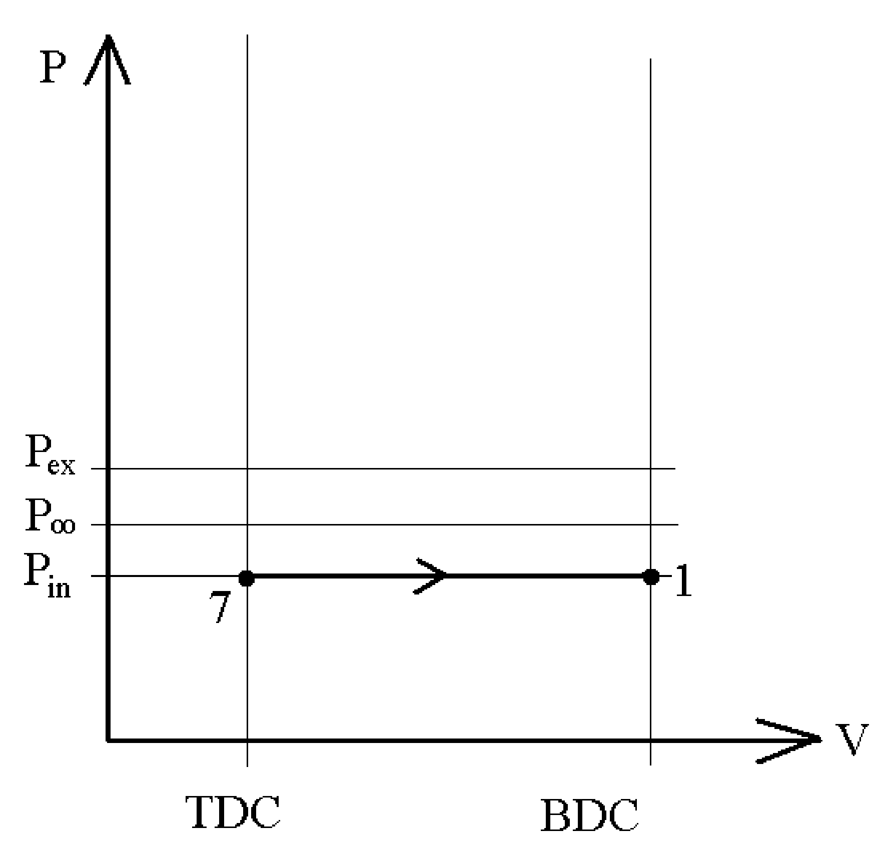
• Fresh fuel/air mixture mixes with residual gases in cylinder.

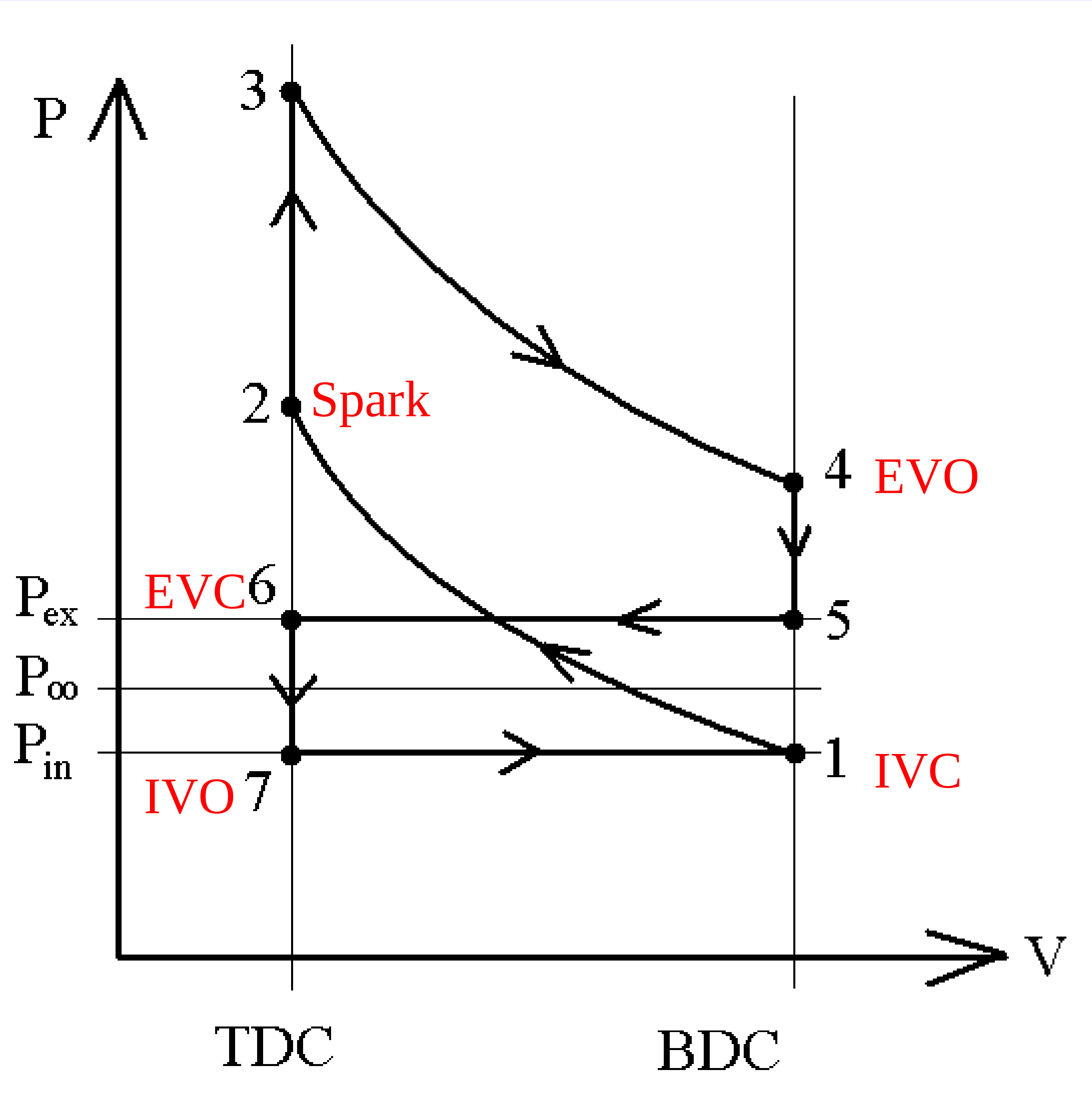
• Work is done by gases. The net work associated with the gas exchange (exhaust + intake) is called "pumping work".

• In ideal cycle, there is no pressure drop across intake valve, so cylinder pressure equals intake manifold pressure.

• In real cycle, there is a pressure drop across intake valve.






P
3
2
Spark
4
EVO
Pex
EVC
6
5
P∞
Pin
1
IVC
IVO
7
V
TDC
BDC

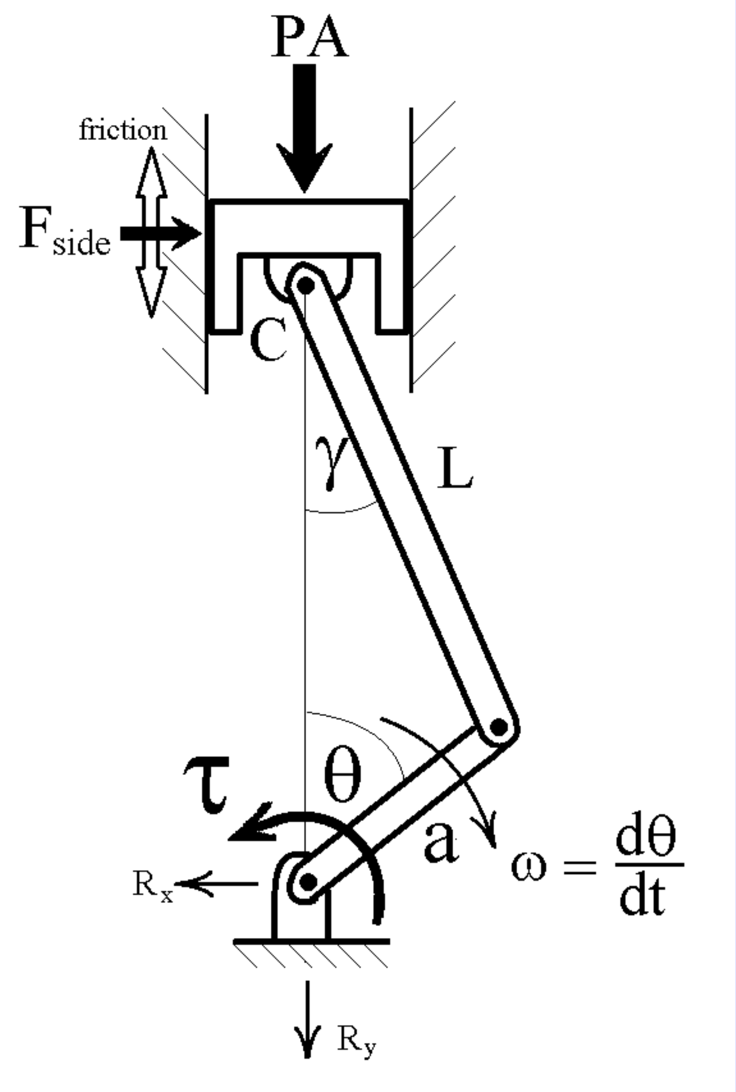
Results: "OttoCycle.xls"

INPUT PARAMS

Vd=	700	cc, Single Cylinder Displacement Volume
r=	10	compression ratio
B/S	1.1	bore to stroke ratio
L/a	3	connecting rod length to crank radius ratio
n=	6	# of Cylinders
N=	2000	RPM, engine speed
Cv=	0.718	kJ/kg/C, constant volume specific heat
R=	0.287	kJ/kg/C, gas constant
Ti=	298	K, Intake Manifold Temperature
Pi=	0.7	atm, Intake Manifold Pressure
Pe=	1.2	atm, Exhaust Manifold Pressure
Qc/(1+AFR)	2730	kJ/kg, heat released per kg mixture
Tinf=	298	K, Ambient Temperature
Pinf=	1	atm, Ambient Pressure
mu=	0.4	friction coefficient

DERIVED QUANTITIES

Vc=	77.8	cc, Clearance Volume
B=	9.9	cm, bore
a=	4.5	cm, crank radius
Lcr=	13.5	cm, connecting rod length
k=	1.40	ratio of specific heats
Cp=	1.005	kJ/kg/C, specific heat at constant pressure
rhoinf=	1.186	kg/m^3, ambient density
rhointake=	0.830	kg/m^3, intake density

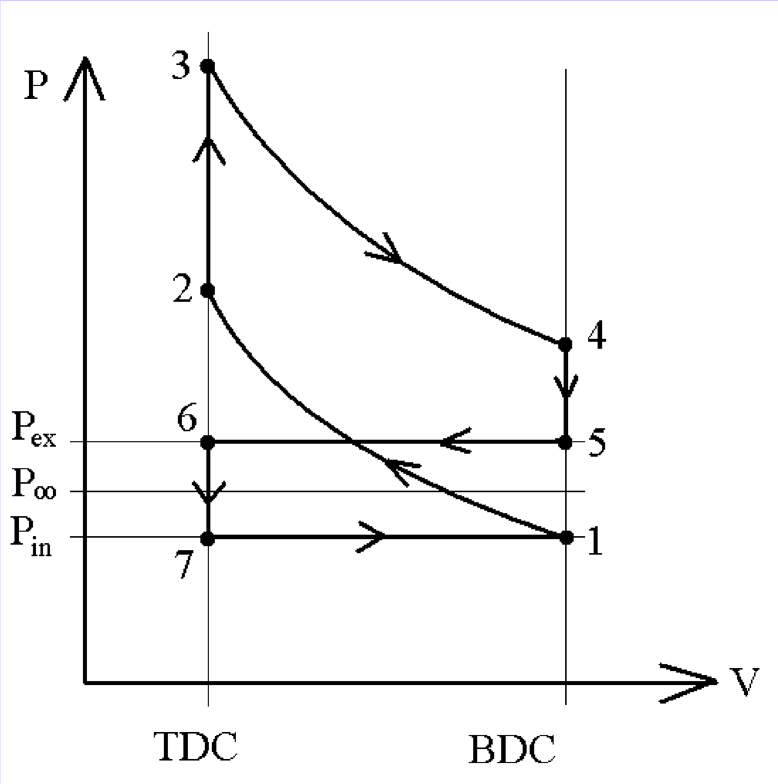


- The initial Volume and Pressure are known, but the TEMPERATURE isn't (fresh gas is mixed with hot products, and the precise amount can't be easily determined beforehand).

- An iterative solution is required… T_1 is "guessed". Then residual gases (state 7) are mixed with inducted air (at Inlet conditions) to set the initial temperature of the next cycle.

Cycle #	Cycle State	Cycle Angle	V (cc)	P (atm)	T (K)	M (kg)
1	1	0	777.8	0.70	298.0	6.46E-04
	2	90	77.8	17.55	747.3	6.46E-04
	3	90	77.8	106.87	4549.5	6.46E-04
	4	180	777.8	4.26	1814.2	6.46E-04
	5	180	777.8	1.20	1263.7	2.61E-04
	6	270	77.8	1.20	1263.7	2.61E-05
	7	270	77.8	0.70	1083.5	1.78E-05
2	1	0	777.8	0.70	327.8	5.87E-04
	2	90	77.8	17.55	822.0	5.87E-04
	3	90	77.8	98.75	4624.3	5.87E-04
	4	180	777.8	3.94	1844.0	5.87E-04
	5	180	777.8	1.20	1313.7	2.51E-04
	6	270	77.8	1.20	1313.7	2.51E-05
	7	270	77.8	0.70	1126.4	1.71E-05
3	1	0	777.8	0.70	330.8	5.82E-04
	2	90	77.8	17.55	829.5	5.82E-04
	3	90	77.8	98.02	4631.8	5.82E-04
	4	180	777.8	3.91	1847.0	5.82E-04
	5	180	777.8	1.20	1318.6	2.50E-04
	6	270	77.8	1.20	1318.6	2.50E-05
	7	270	77.8	0.70	1130.6	1.70E-05
4	1	0	777.8	0.70	331.1	5.81E-04
	2	90	77.8	17.55	830.3	5.81E-04
	3	90	77.8	97.95	4632.5	5.81E-04
	4	180	777.8	3.91	1847.3	5.81E-04
	5	180	777.8	1.20	1319.1	2.50E-04
	6	270	77.8	1.20	1319.1	2.50E-05
	7	270	77.8	0.70	1131.1	1.70E-05

Converged Solution:



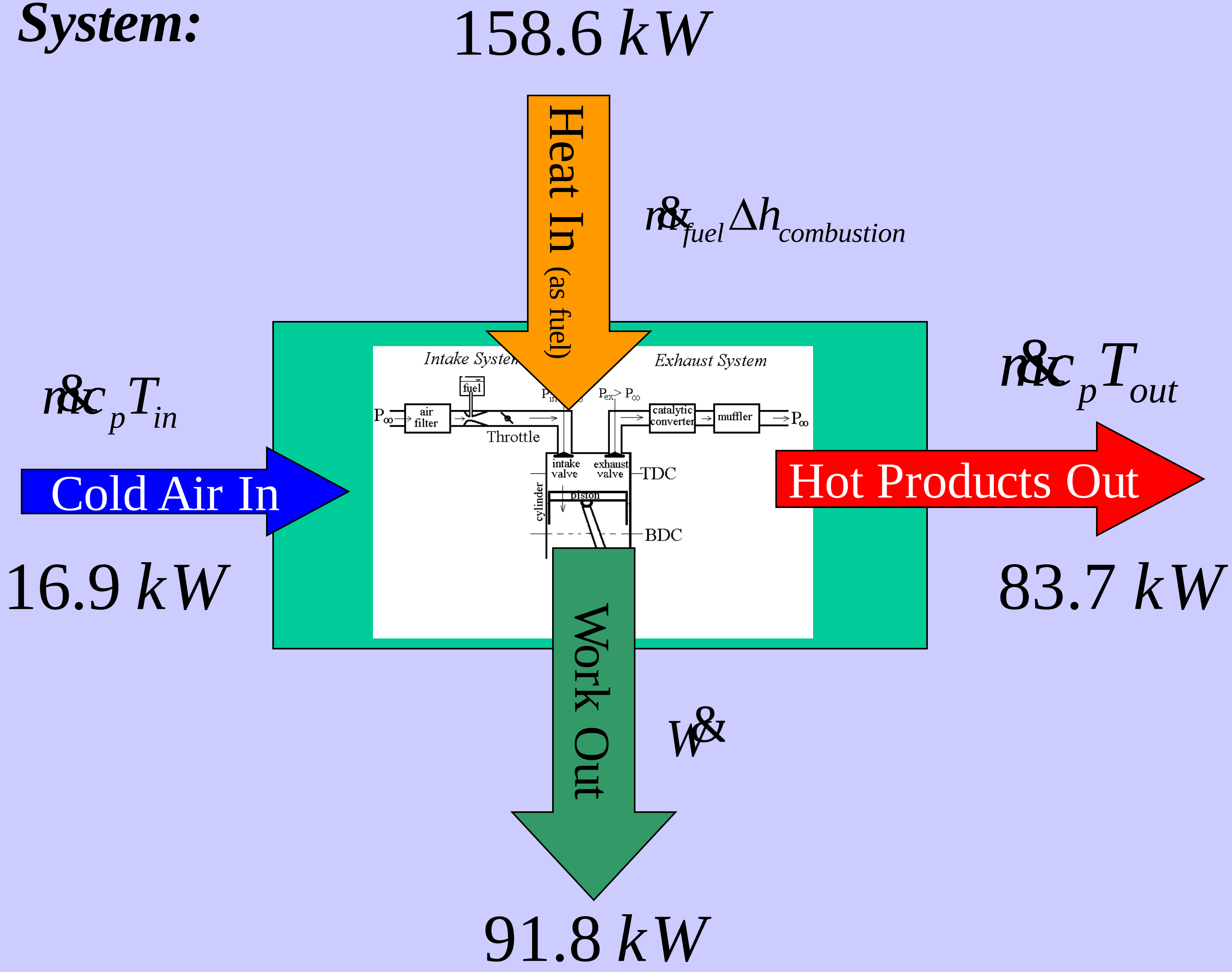
STATE TABLE

Cycle State	Cycle Angle	V (cc)	P (atm)	T (K)	M (kg)
1	0	777.8	0.70	331.1	5.81E-04
2	90	77.8	17.55	830.4	5.81E-04
3	90	77.8	97.94	4632.6	5.81E-04
4	180	777.8	3.91	1847.3	5.81E-04
5	180	777.8	1.20	1319.2	2.50E-04
6	270	77.8	1.20	1319.2	2.50E-05
7	270	77.8	0.70	1131.1	1.70E-05

PROCESS TABLE

Process	Description	Q (kJ)	W (kJ)	DM (g)
1-2	Compression	0	-0.208	0
2-3	Combustion	1.586	0	0
3-4	Power Stroke	0	1.162	0
4-5	BlowDown	0	0	-0.331
5-6	Exhaust Stroke	0	-0.085	-0.225
6-7	Valve Overlap	0	0	-0.008
7-1	Intake Stroke	0	0.050	0.564
sum		***1.586***	***0.918***	***0***

Engine as Steady-State Open System:

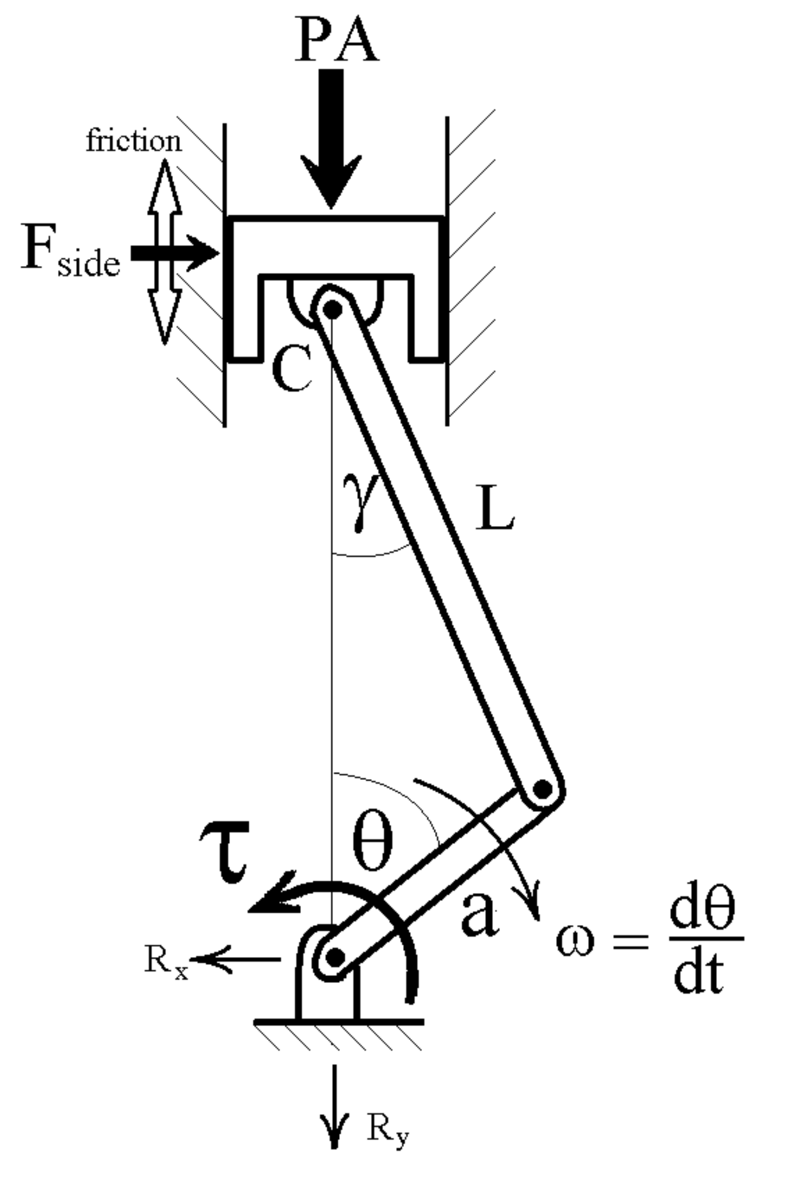


ENGINE PERFORMANCE

Heat Input =	158.6	kW
Enthalpy Flux In =	16.9	kW
Enthalpy Flux Out=	83.7	kW
Work Output=	91.8	kW
Thermal Efficiency=	0.579	
Maximum Possible Efficiency=	0.929	
2nd Law Efficiency=	0.623	
Mass Flow Rate =	0.0564	kg/s
Volumetric Flow Rate =	2853.9	Liters/min
Texit =	1477	K

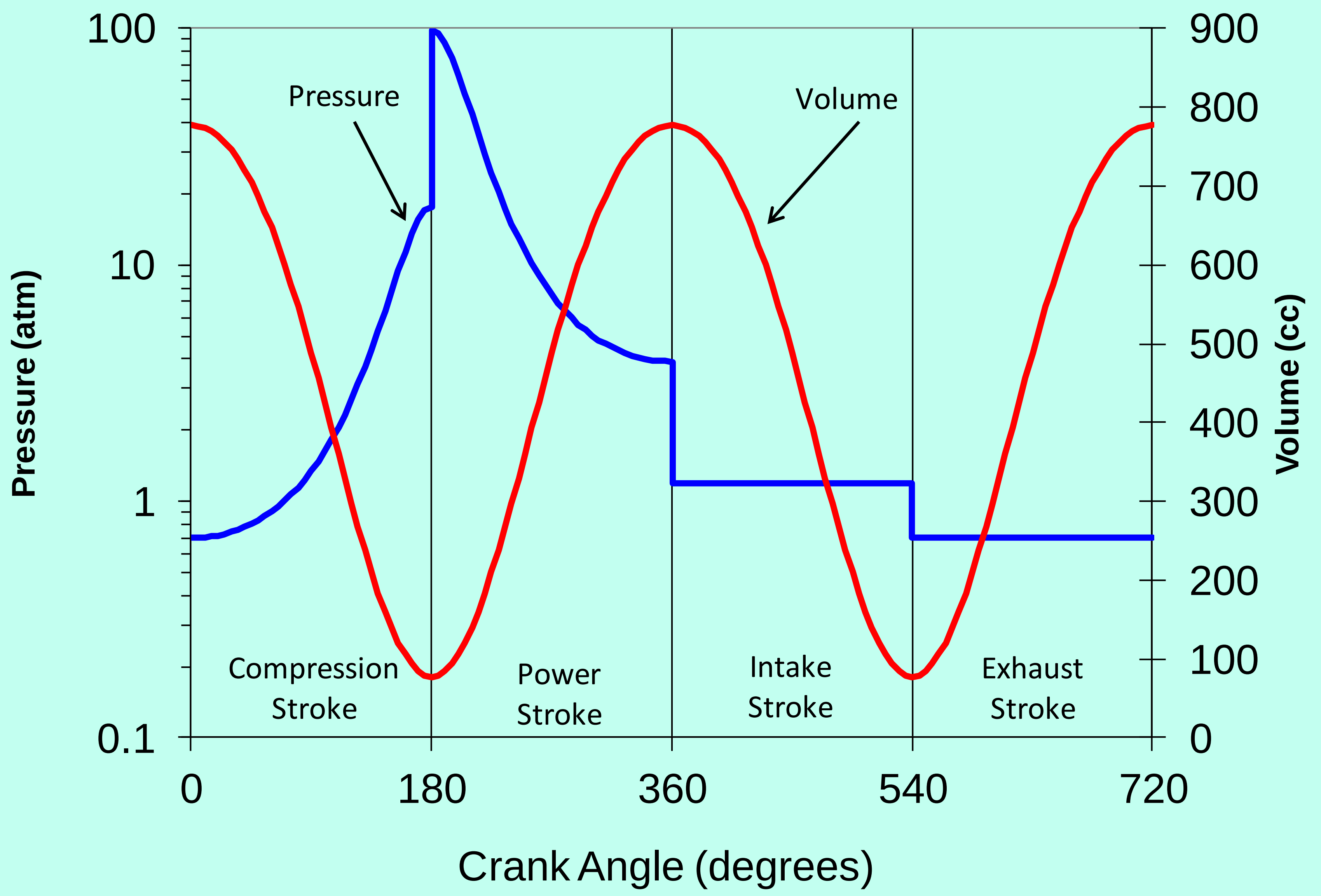
States as a function of crank angle

- Calorically perfect gas model (c_v = constant) allows for analysis of cycle by direct integration from state to state.
- While not necessary to analyze the over-all process, it is insightful to calculate all quantities as a function of crank angle.
- Here we go!

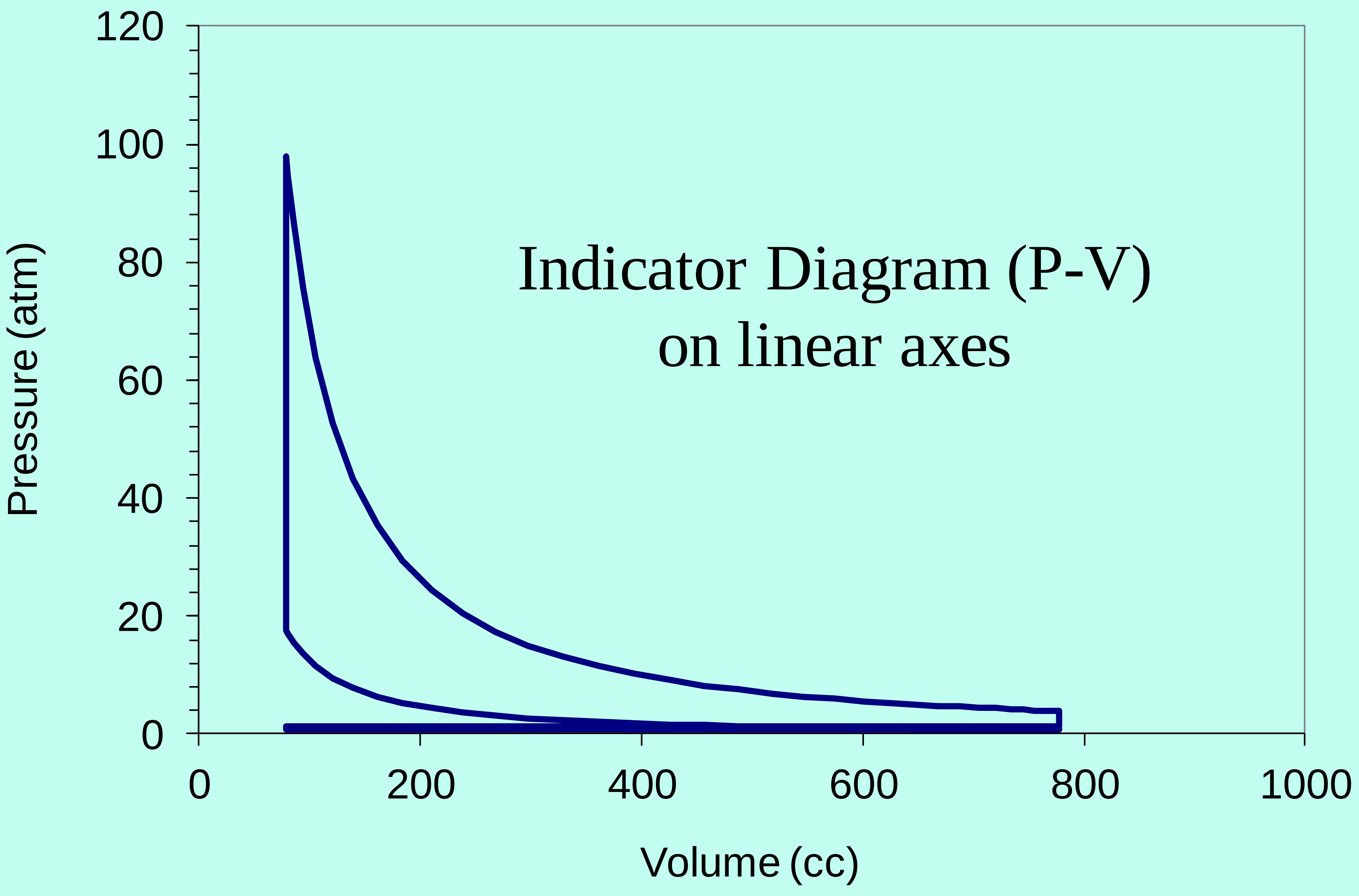


States as a function of crank angle

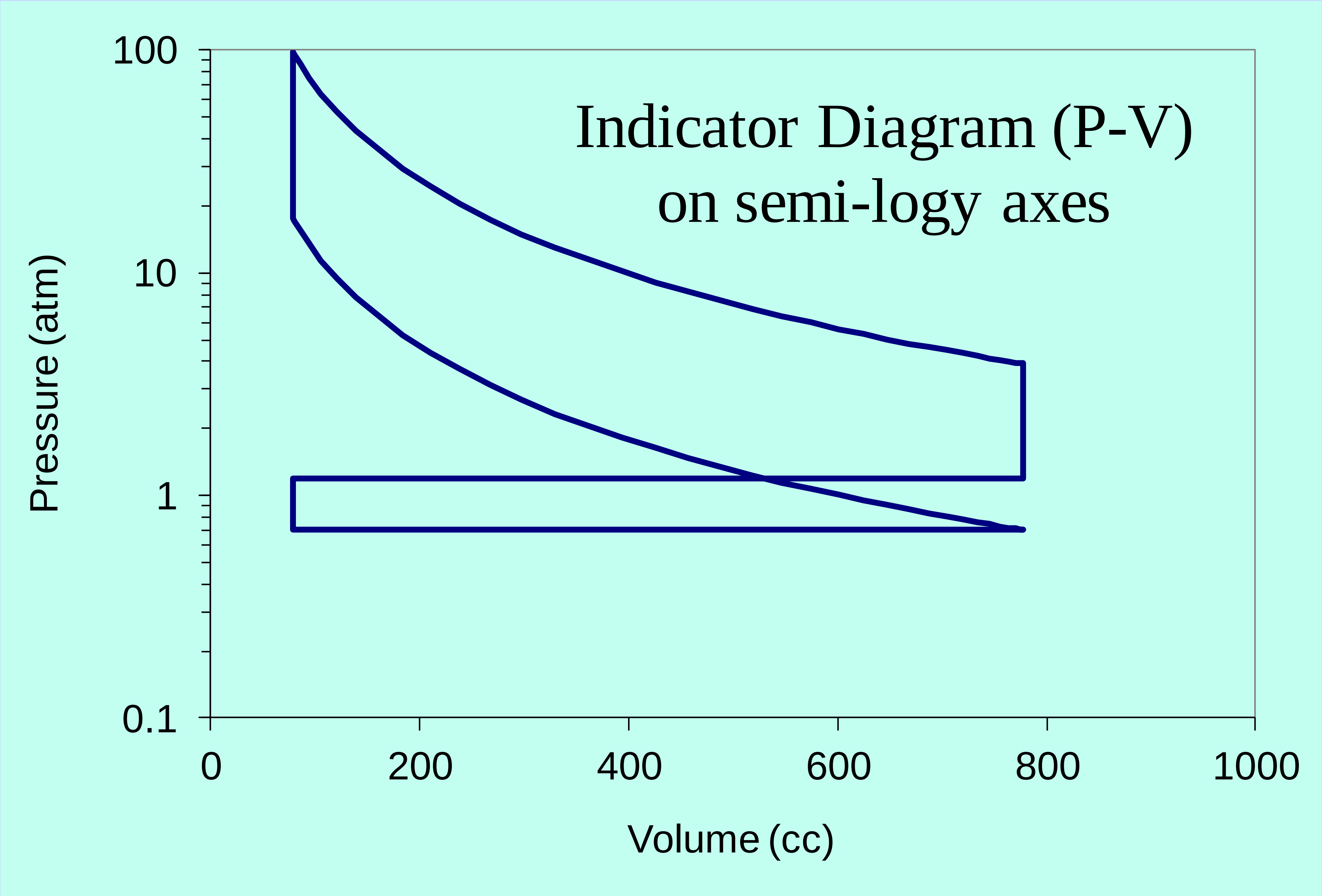
												FORCES				
Crank Angle (alpha, deg)	Stroke	time (msec)	theta (deg)	gamma (deg)	h (cm)	Vp = -dh/dt (cm/s)	Volume (cc)	Pressure (atm)	Temperature (K)	Mass (g)	mdot	PA (kN)	Fside (kN)	Friction (kN)	Frod (kN)	Torque (kN-m)
0	0.00	0.00	180.00	0.00	9.03	0.00	777.8	0.7	331.1	0.581		0.550	0.000	0.000	0.550	0.000
5	0.03	0.42	175.00	1.66	9.02	55.04	776.9	0.7011	331.3	0.581	0	0.551	0.016	-0.006	0.557	0.001
10	0.06	0.83	170.00	3.32	8.99	110.22	774.2	0.7045	331.7	0.581	0	0.553	0.033	-0.013	0.567	0.003
15	0.08	1.25	165.00	4.95	8.93	165.67	769.8	0.7102	332.5	0.581	0	0.558	0.050	-0.020	0.580	0.005
20	0.11	1.67	160.00	6.55	8.85	221.48	763.5	0.7184	333.6	0.581	0	0.564	0.068	-0.027	0.595	0.006
25	0.14	2.08	155.00	8.10	8.74	277.72	755.5	0.7291	335.0	0.581	0	0.572	0.086	-0.035	0.613	0.008
30	0.17	2.50	150.00	9.59	8.62	334.43	745.6	0.7427	336.7	0.581	0	0.583	0.106	-0.042	0.634	0.010
35	0.19	2.92	145.00	11.02	8.46	391.55	733.9	0.7593	338.9	0.581	0	0.596	0.126	-0.050	0.659	0.012
40	0.22	3.33	140.00	12.37	8.29	448.99	720.3	0.7794	341.4	0.581	0	0.612	0.147	-0.059	0.687	0.014
45	0.25	3.75	135.00	13.63	8.09	506.54	704.8	0.8034	344.4	0.581	0	0.631	0.169	-0.068	0.719	0.017
50	0.28	4.17	130.00	14.79	7.87	563.92	687.6	0.8318	347.8	0.581	0	0.653	0.193	-0.077	0.755	0.020

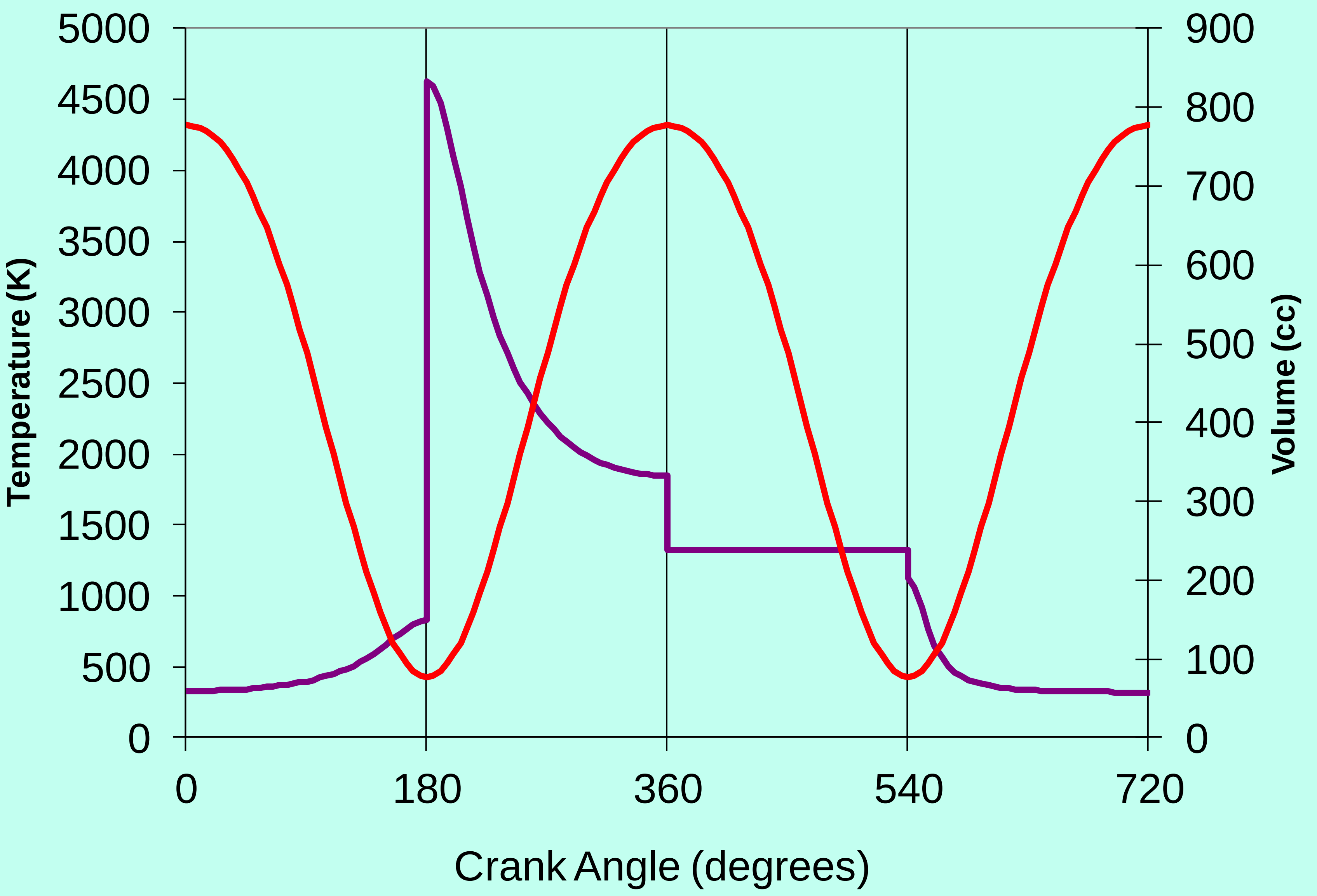


Pressure (atm)
100
10
1
0.1
Volume (cc)
900
800
700
600
500
400
300
200
100
0
Pressure
Volume
Compression
Stroke
Power
Stroke
Intake
Stroke
Exhaust
Stroke
0
180
360
540
720
Crank Angle (degrees)

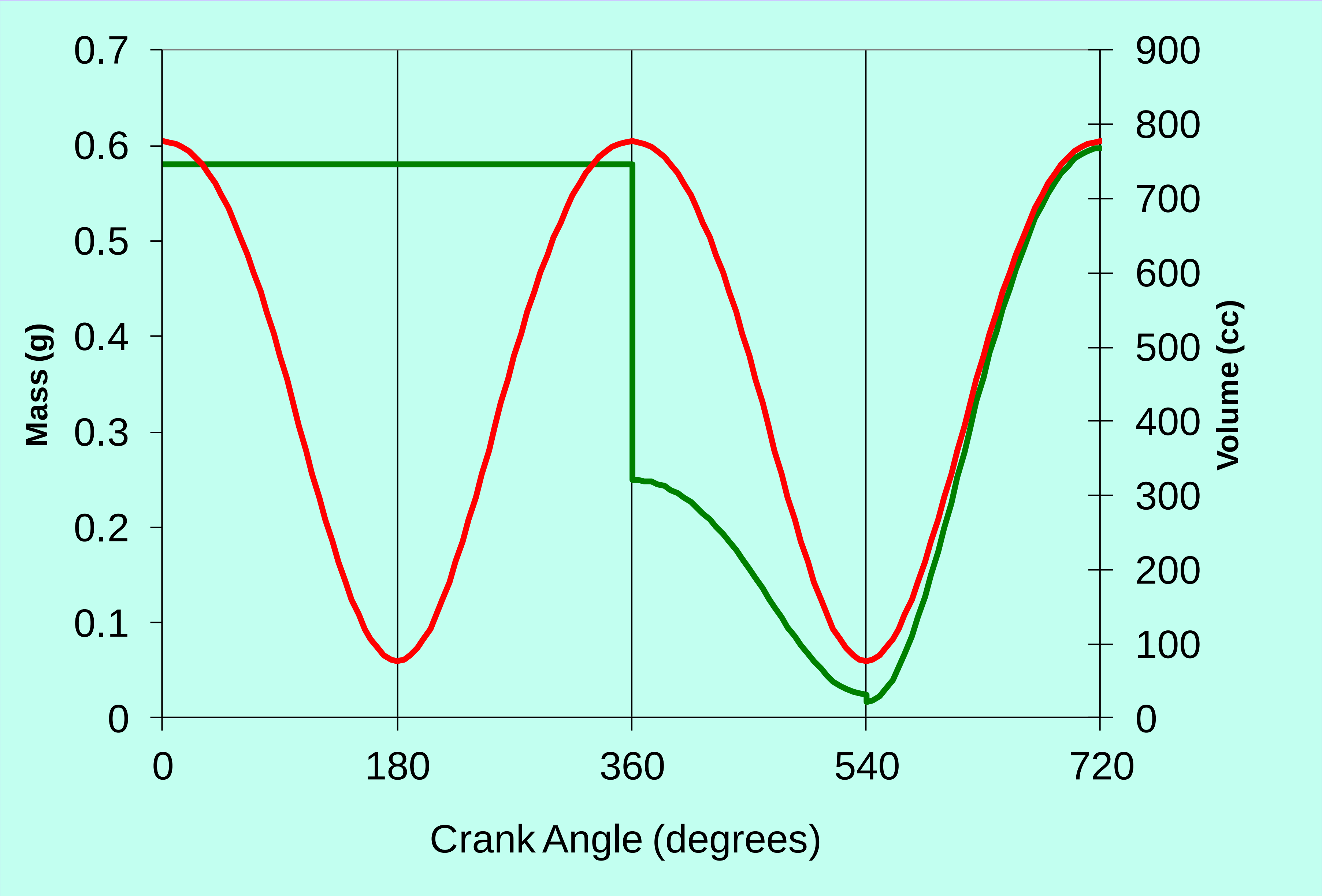


Indicator Diagram (P-V)
on linear axes
Pressure (atm)
Volume (cc)
0
20
40
60
80
100
120
0
200
400
600
800
1000

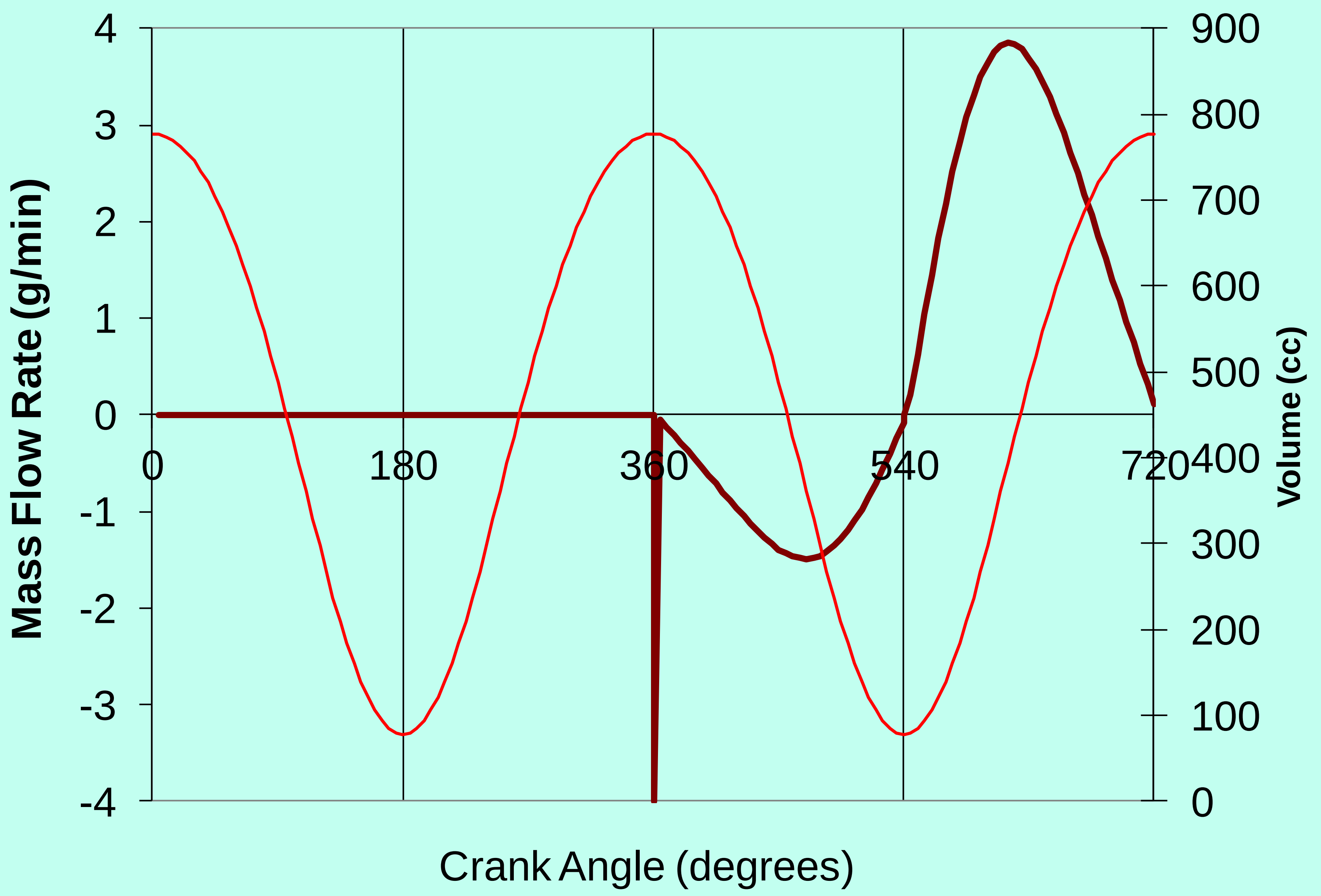

Indicator Diagram (P-V)
on semi-logy axes
Pressure (atm)
100
10
1
0.1
0
200
400
600
800
1000
Volume (cc)



5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Temperature (K)
900
800
700
600
500
400
300
200
100
0
Volume (cc)
0
180
360
540
720
Crank Angle (degrees)

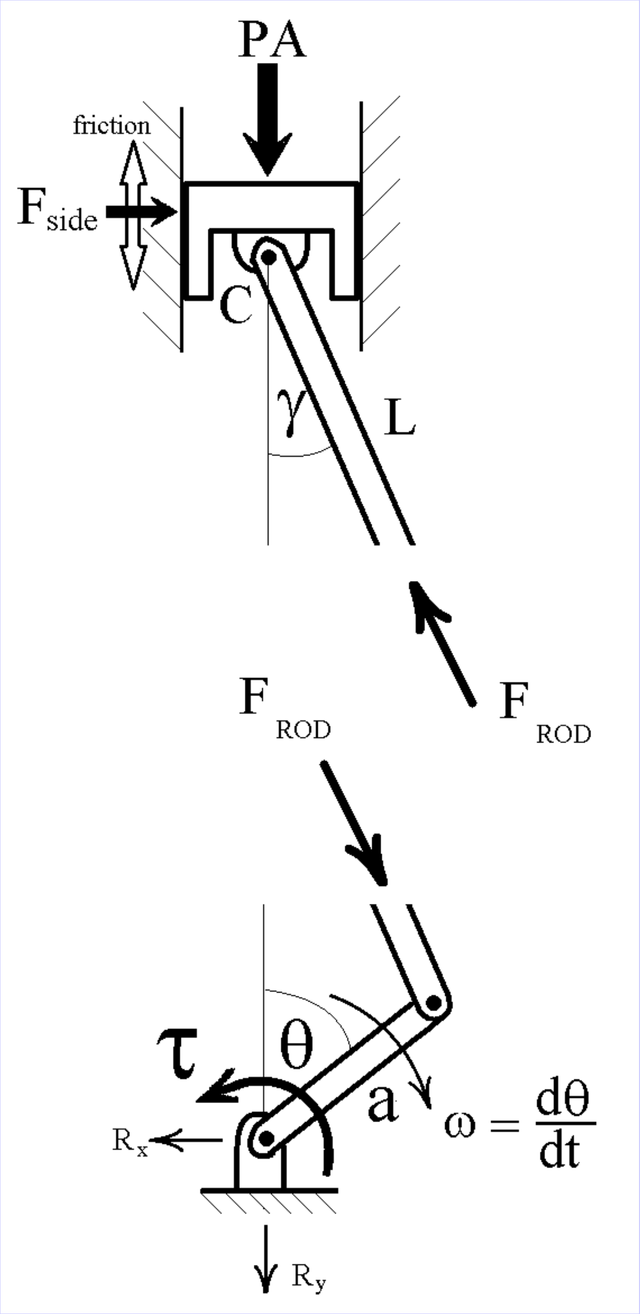


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass (g)
900
800
700
600
500
400
300
200
100
0
Volume (cc)
0
180
360
540
720
Crank Angle (degrees)



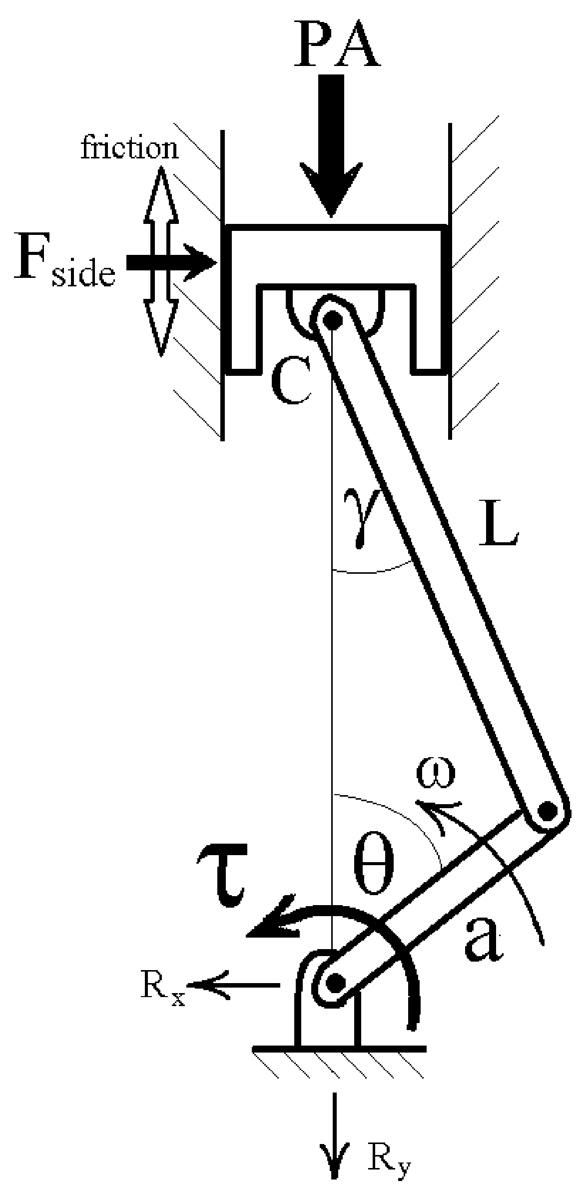
Mass Flow Rate (g/min)
4
3
2
1
0
-1
-2
-3
-4
0
180
360
540
720
900
800
700
600
500
400
300
200
100
0
Volume (cc)
Crank Angle (degrees)

Forces and Torques

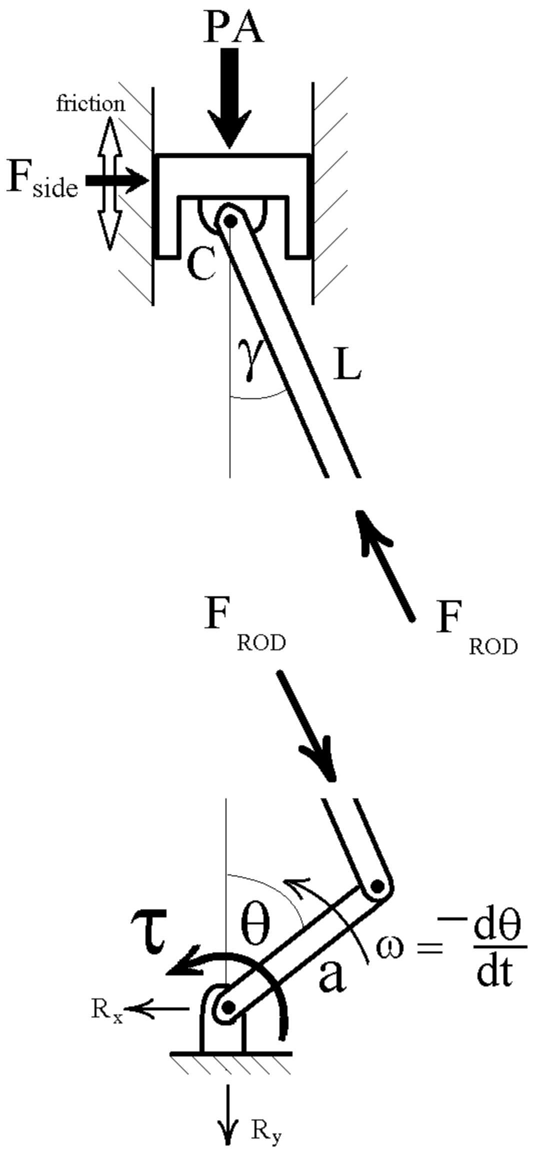


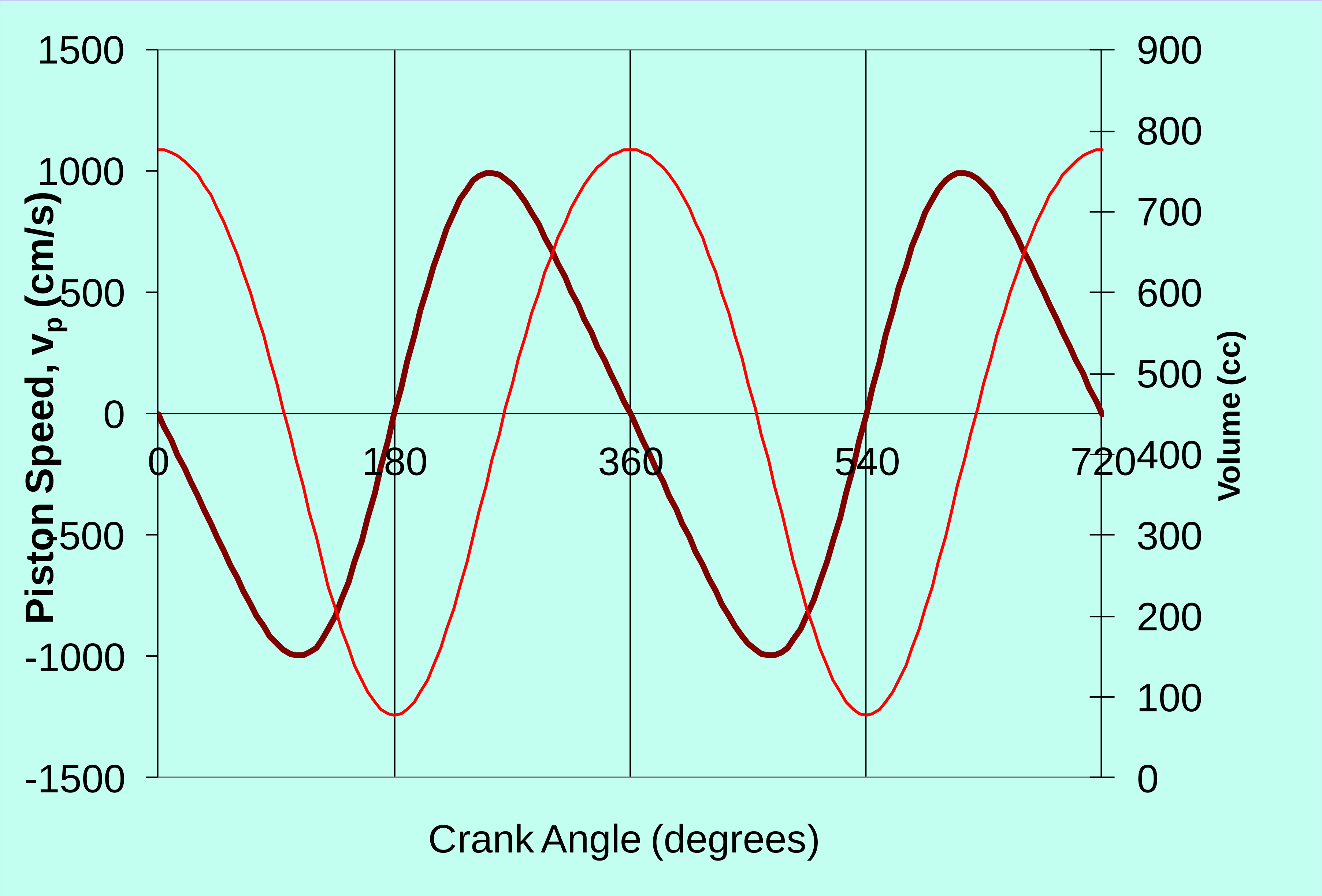
Mechanics Quiz:

"Converting linear to rotational motion"

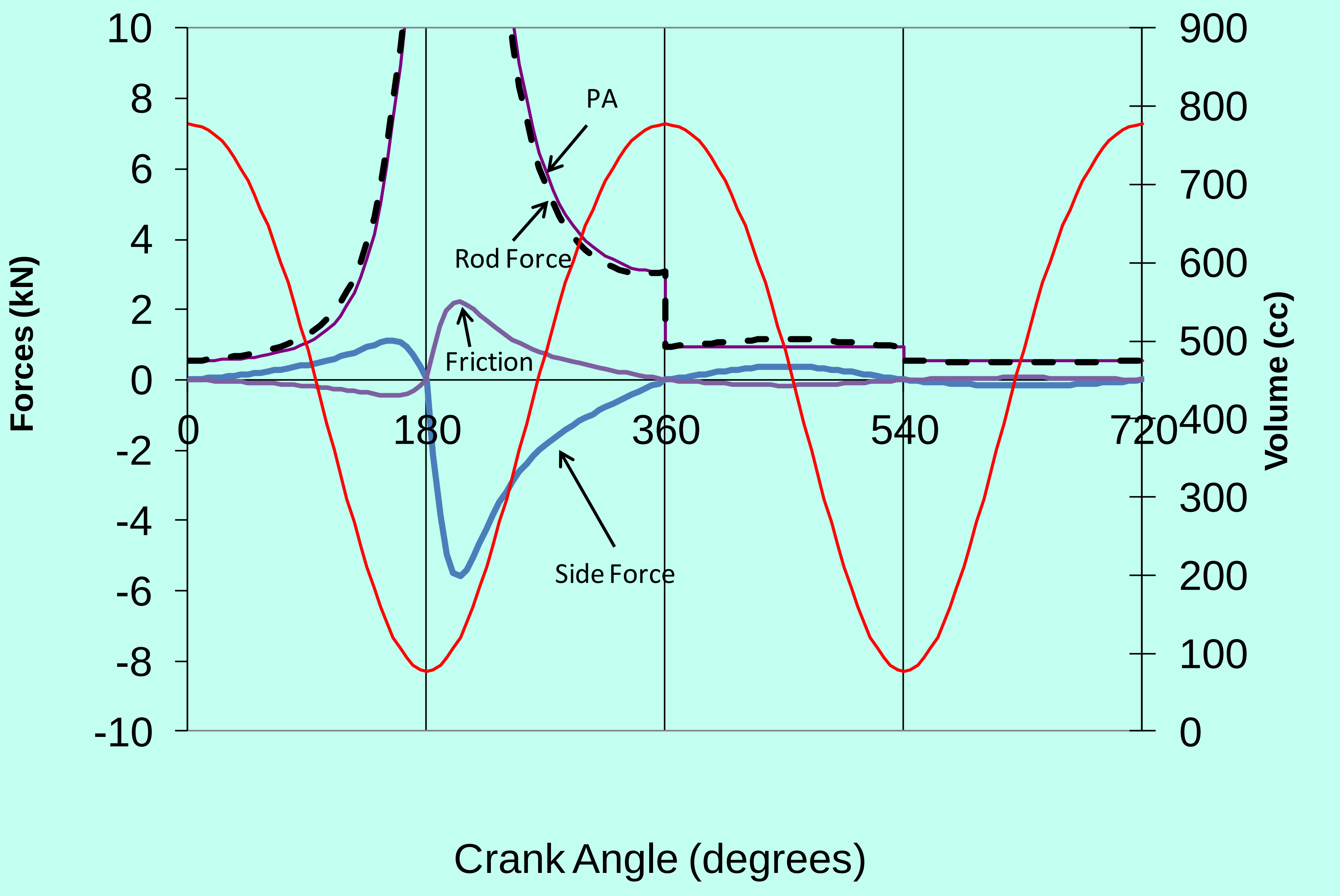


The piston/cylinder assembly shown consists of a piston onto which a 50 kN load is applied, and a connecting rod (of length L) that drives a crank arm (of length a) that rotates at a constant angular speed with a restraining torque (τ). Assume the friction force is proportional to the side force with a friction coefficient, μ. Neglecting inertial effects (i.e. treat all members as being massless), derive expressions for the side force acting on the piston and the reaction forces and torque on the crank shaft in terms of the crank angle (θ) and member lengths.

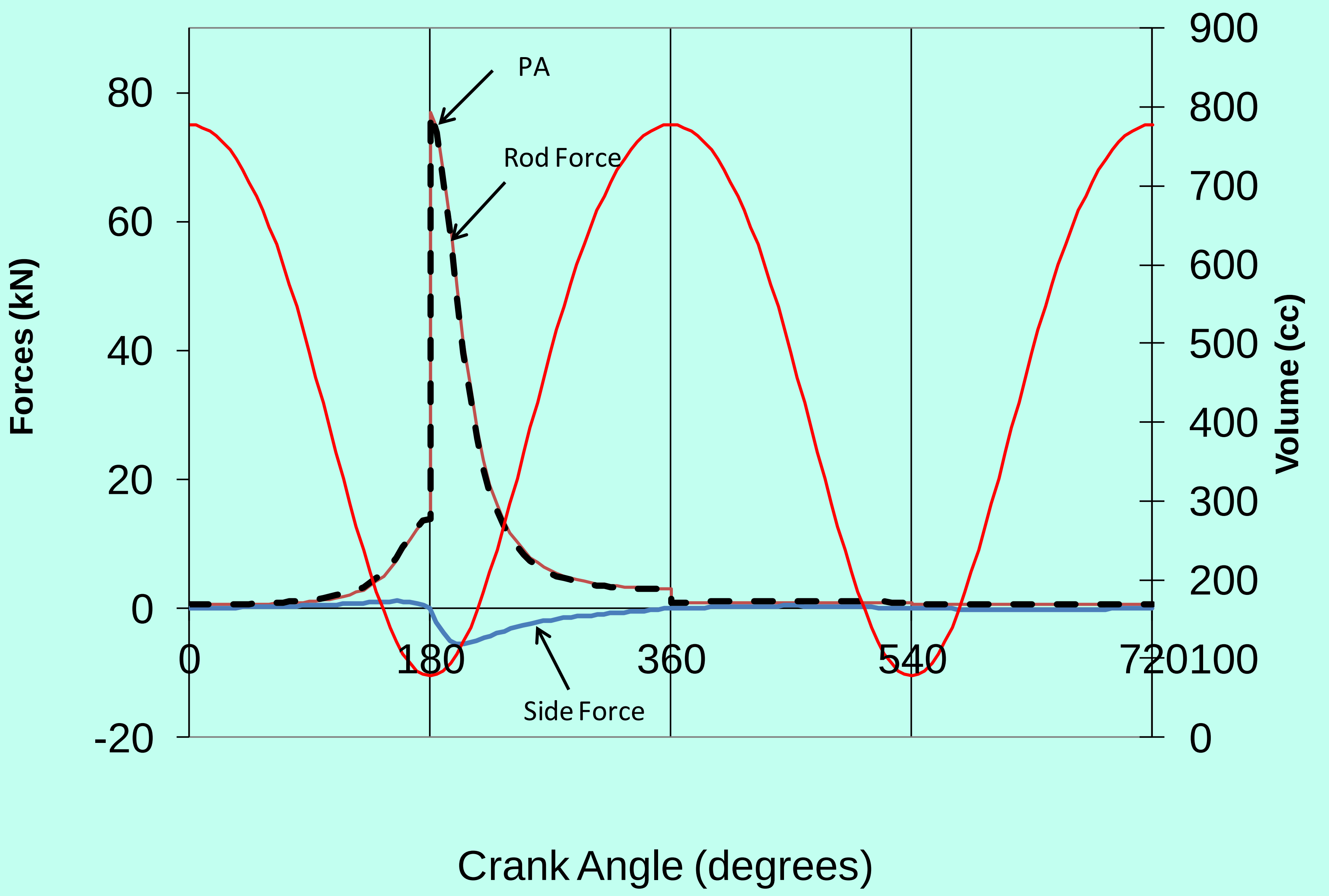

PA
friction
F_{side}
C
γ
L
F_{ROD}
F_{ROD}
τ
θ
a
$\omega = -\frac{d\theta}{dt}$
R_x
R_y



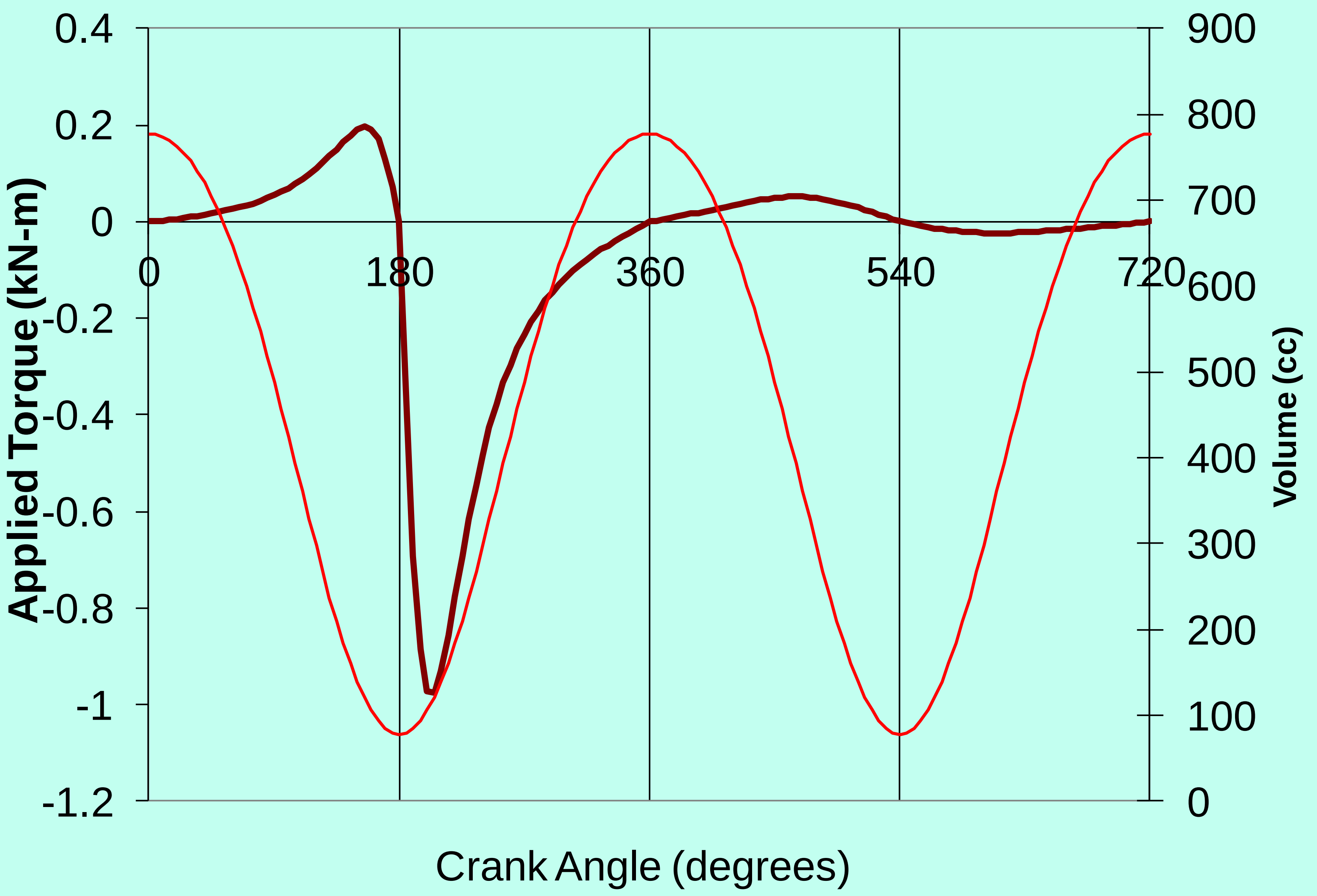
1500
1000
500
0
-500
-1000
-1500
Piston Speed, v_p (cm/s)
900
800
700
600
500
400
300
200
100
0
Volume (cc)
0
180
360
540
720
Crank Angle (degrees)



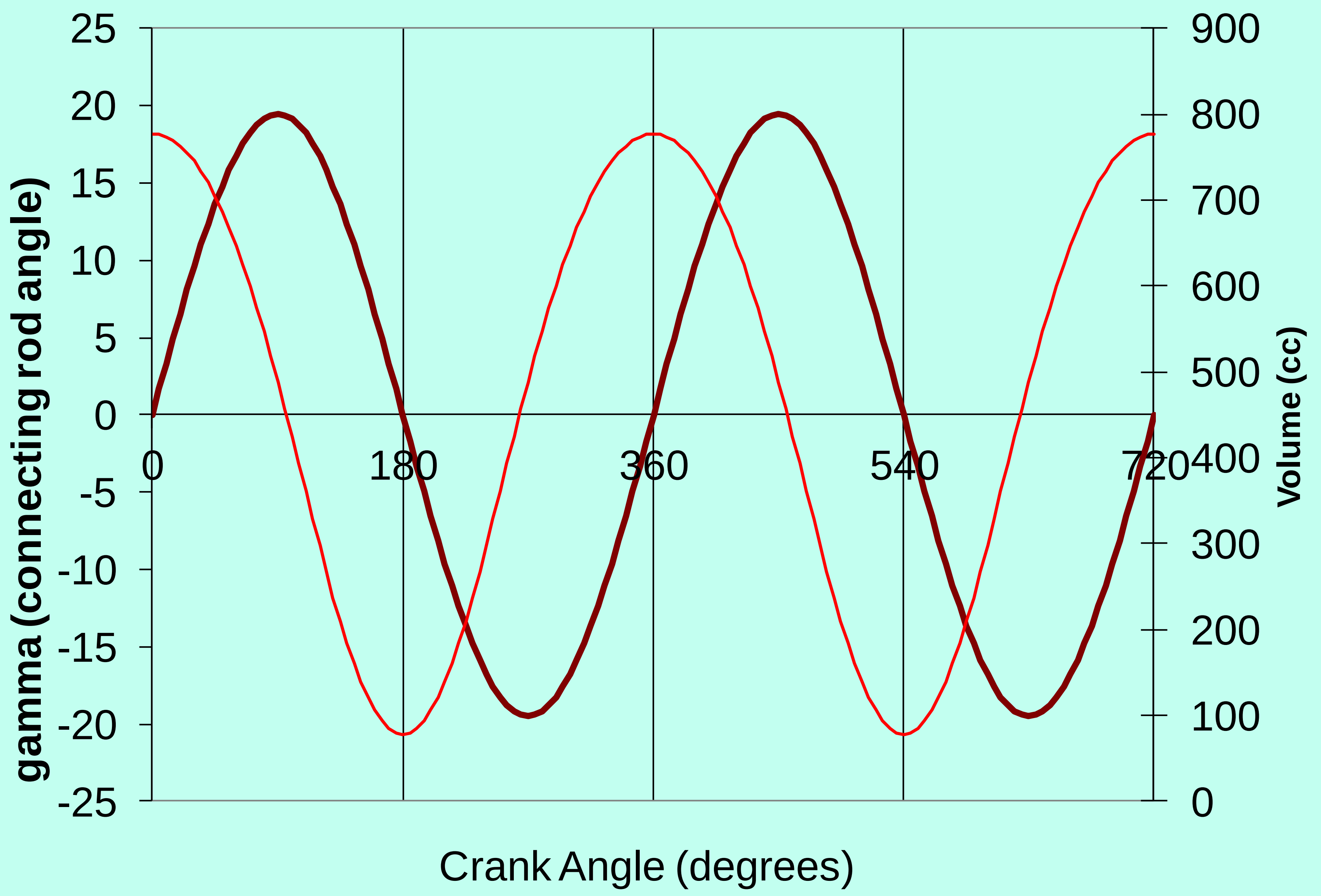
10
8
6
4
2
0
-2
-4
-6
-8
-10
Forces (kN)
900
800
700
600
500
400
300
200
100
0
Volume (cc)
0
180
360
540
720
PA
Rod Force
Friction
Side Force
Crank Angle (degrees)



PA
Rod Force
Side Force
80
60
40
20
0
-20
0
180
360
540
720
900
800
700
600
500
400
300
200
100
0
Forces (kN)
Volume (cc)
Crank Angle (degrees)

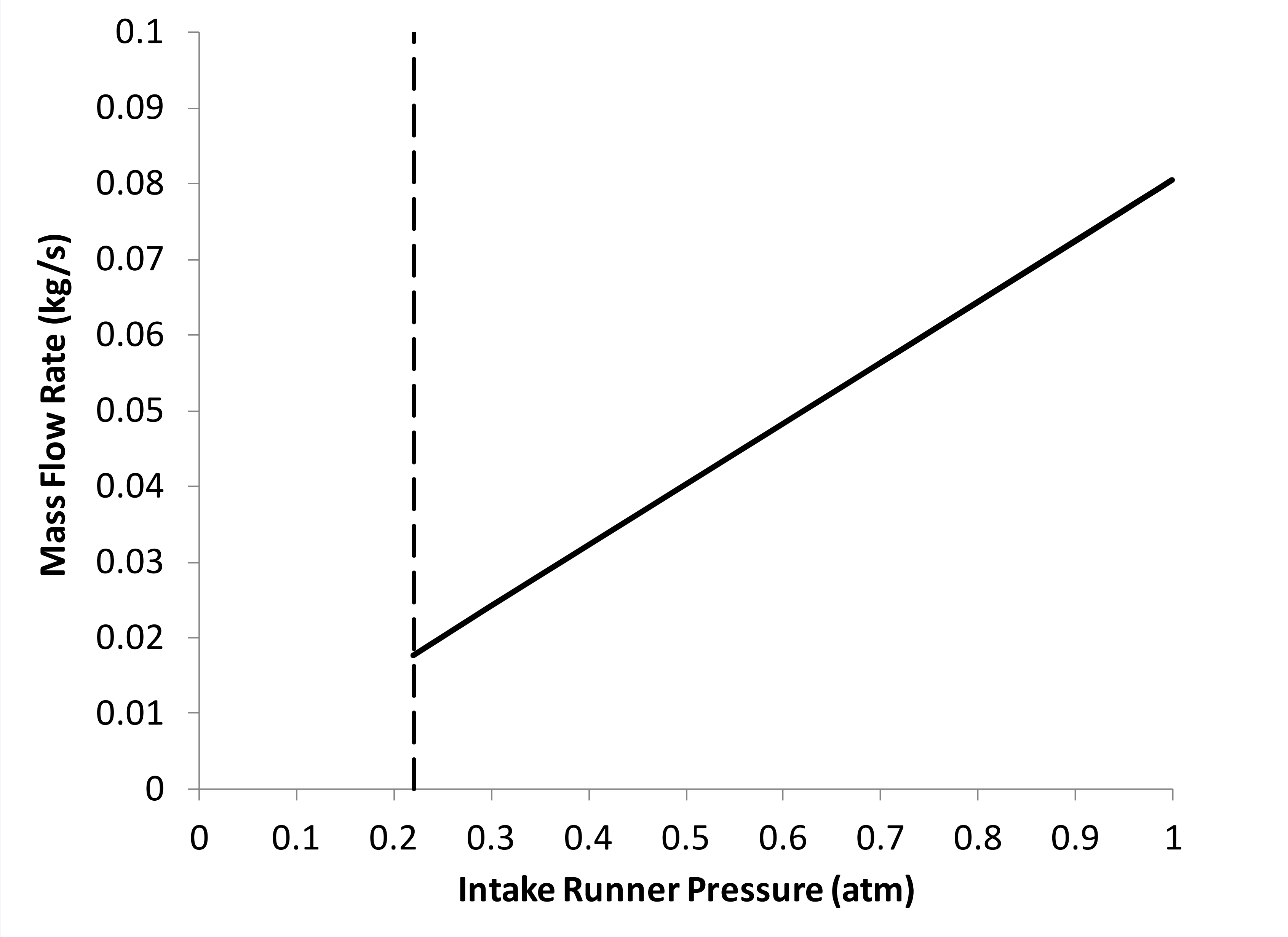


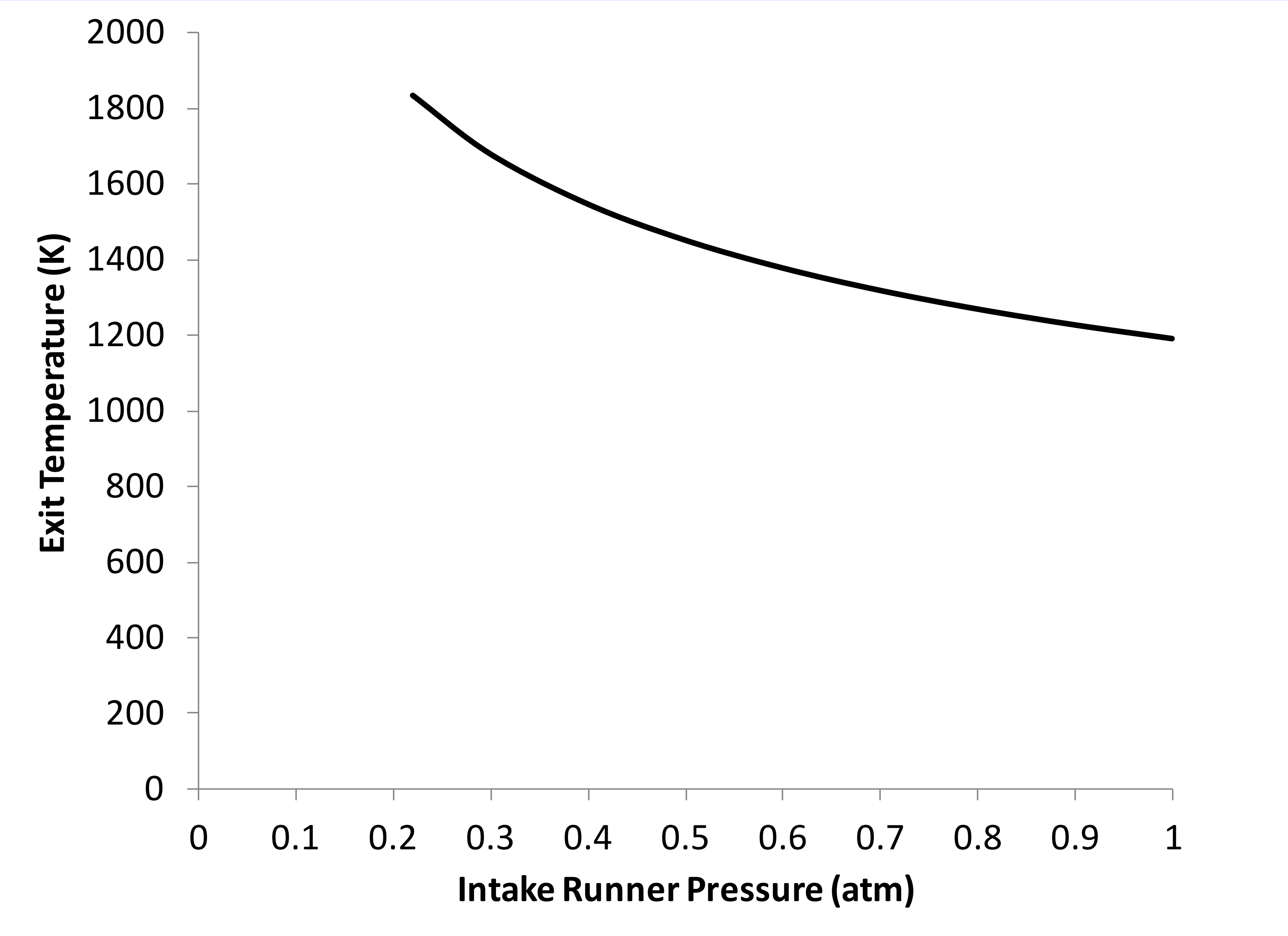
Applied Torque (kN-m)
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
0
180
360
540
720
Crank Angle (degrees)
Volume (cc)
900
800
700
600
500
400
300
200
100
0


gamma (connecting rod angle)
Volume (cc)
Crank Angle (degrees)
25
20
15
10
5
0
-5
-10
-15
-20
-25
0
180
360
540
720
900
800
700
600
500
400
300
200
100
0

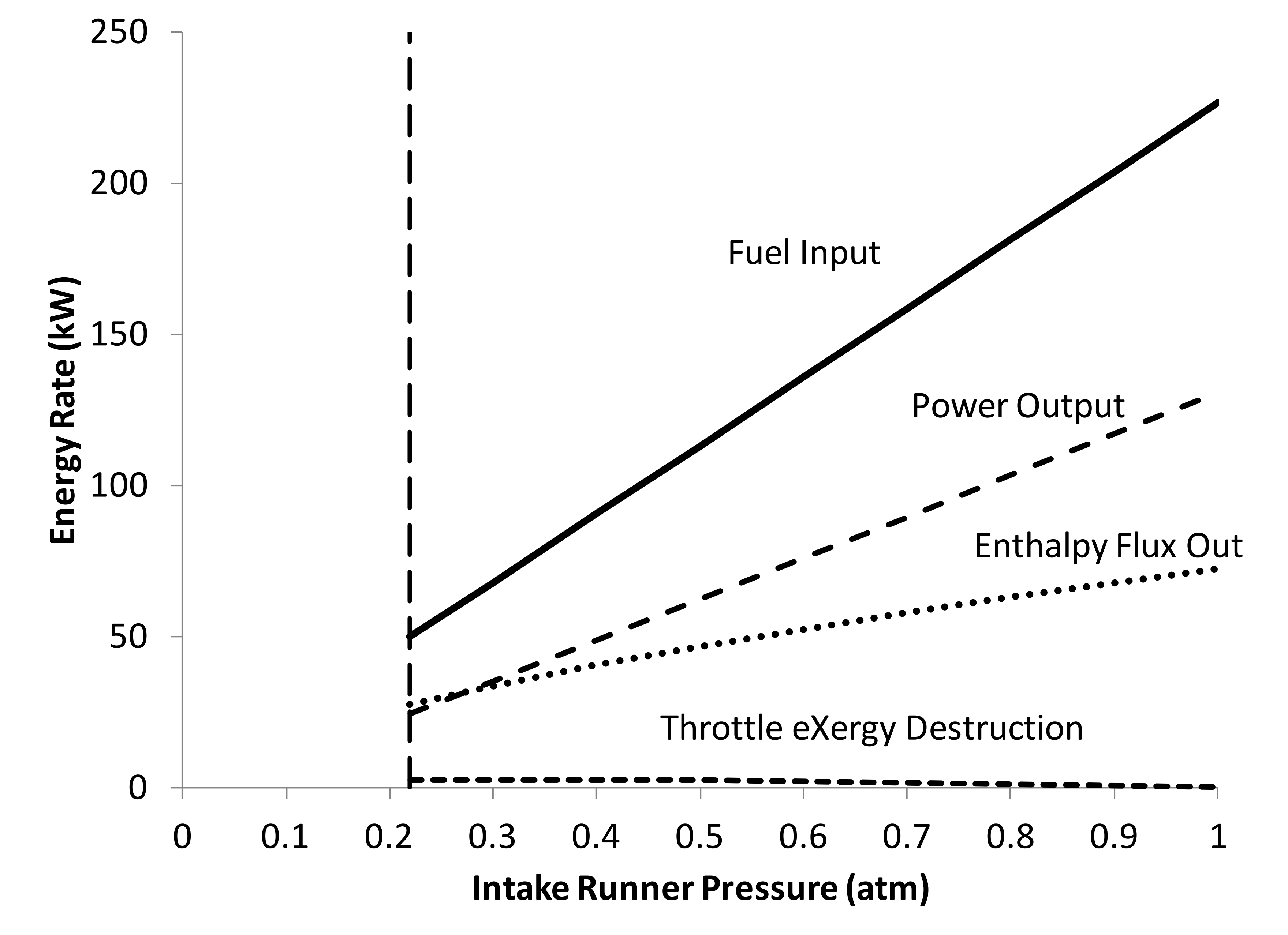
Effect of Throttling on Engine Performance

Pintake (atm)=	0.300	0.400	0.500	0.600	0.700	0.800	0.900	1.000	0.700
Heat Input (kW) =	68.0	90.6	113.3	136.0	158.6	181.3	203.9	226.6	158.6
Enthalpy Flux In (kW)	7.2	9.6	12.1	14.5	16.9	19.3	21.7	24.1	16.9
Enthalpy Flux Out (kW) =	40.0	51.5	62.9	74.4	85.8	97.3	108.7	120.2	85.8
Work Output (kW)	35.2	48.8	62.4	76.1	89.7	103.3	116.9	130.6	89.7
Thermal Efficiency=	0.518	0.539	0.551	0.560	0.565	0.570	0.573	0.576	0.565
Maximum Possible Efficiency=	0.929	0.929	0.929	0.929	0.929	0.929	0.929	0.929	0.929
2nd Law Efficiency=	0.558	0.580	0.594	0.603	0.609	0.614	0.618	0.621	0.609
Mass Flow Rate (kg/sec)	0.024	0.032	0.040	0.048	0.056	0.064	0.073	0.081	0.056
Volumetric Flow Rate (LPM)	1223	1631	2039	2446	2854	3262	3669	4077	2854
Texit (K)	1648	1589	1554	1531	1514	1502	1492	1484	1514

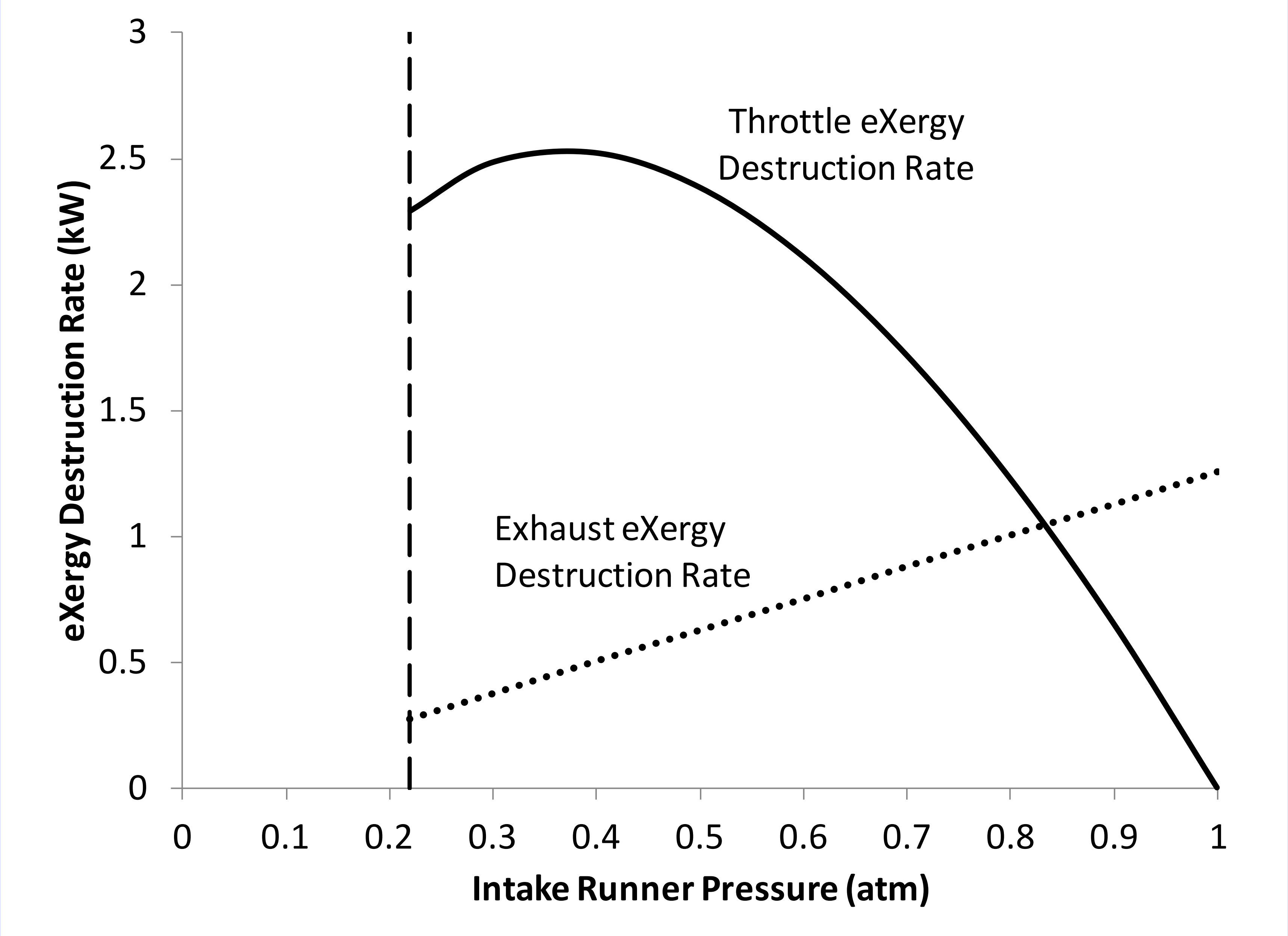

Mass Flow Rate (kg/s)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Intake Runner Pressure (atm)

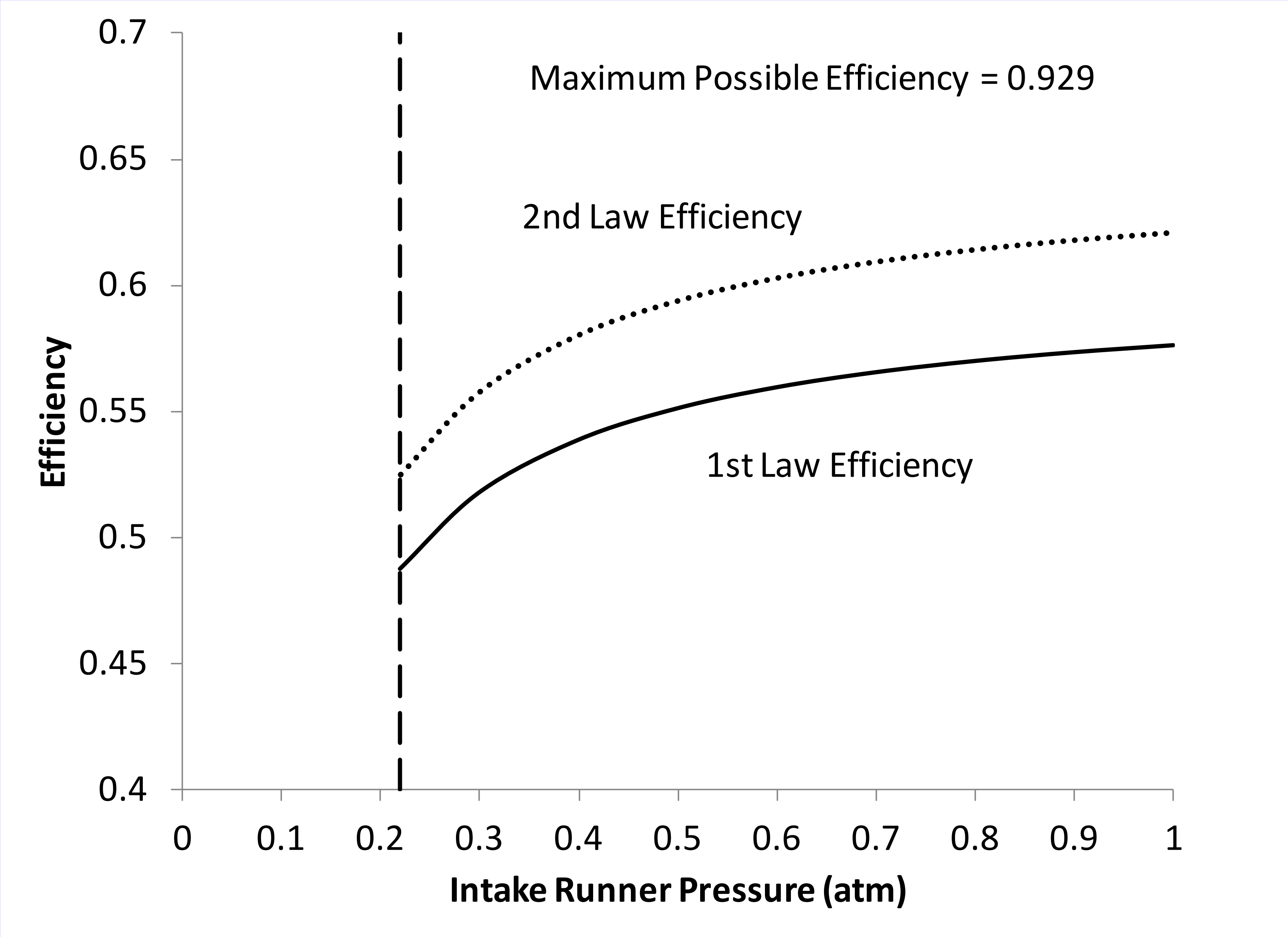


Exit Temperature (K)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Intake Runner Pressure (atm)

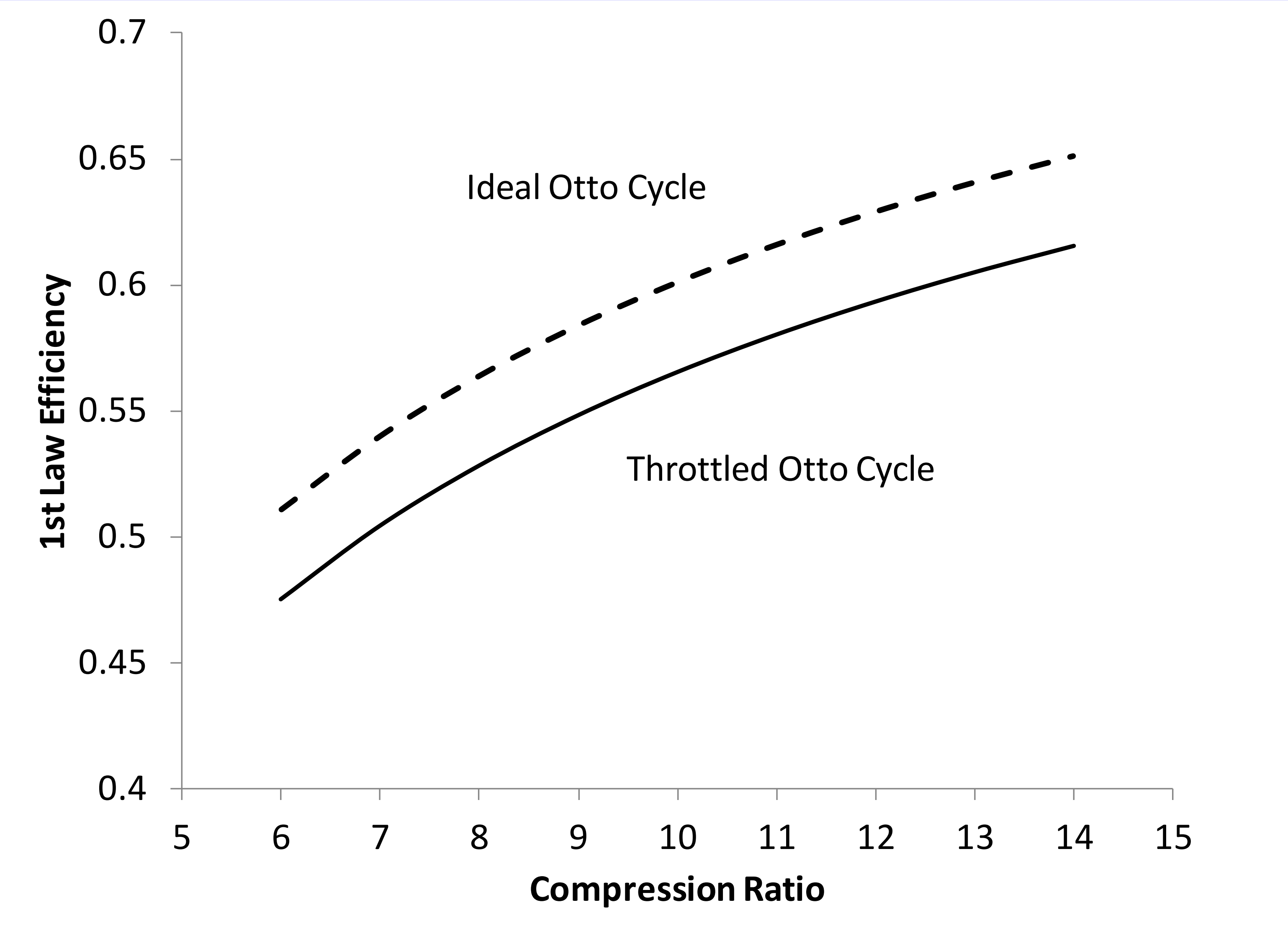


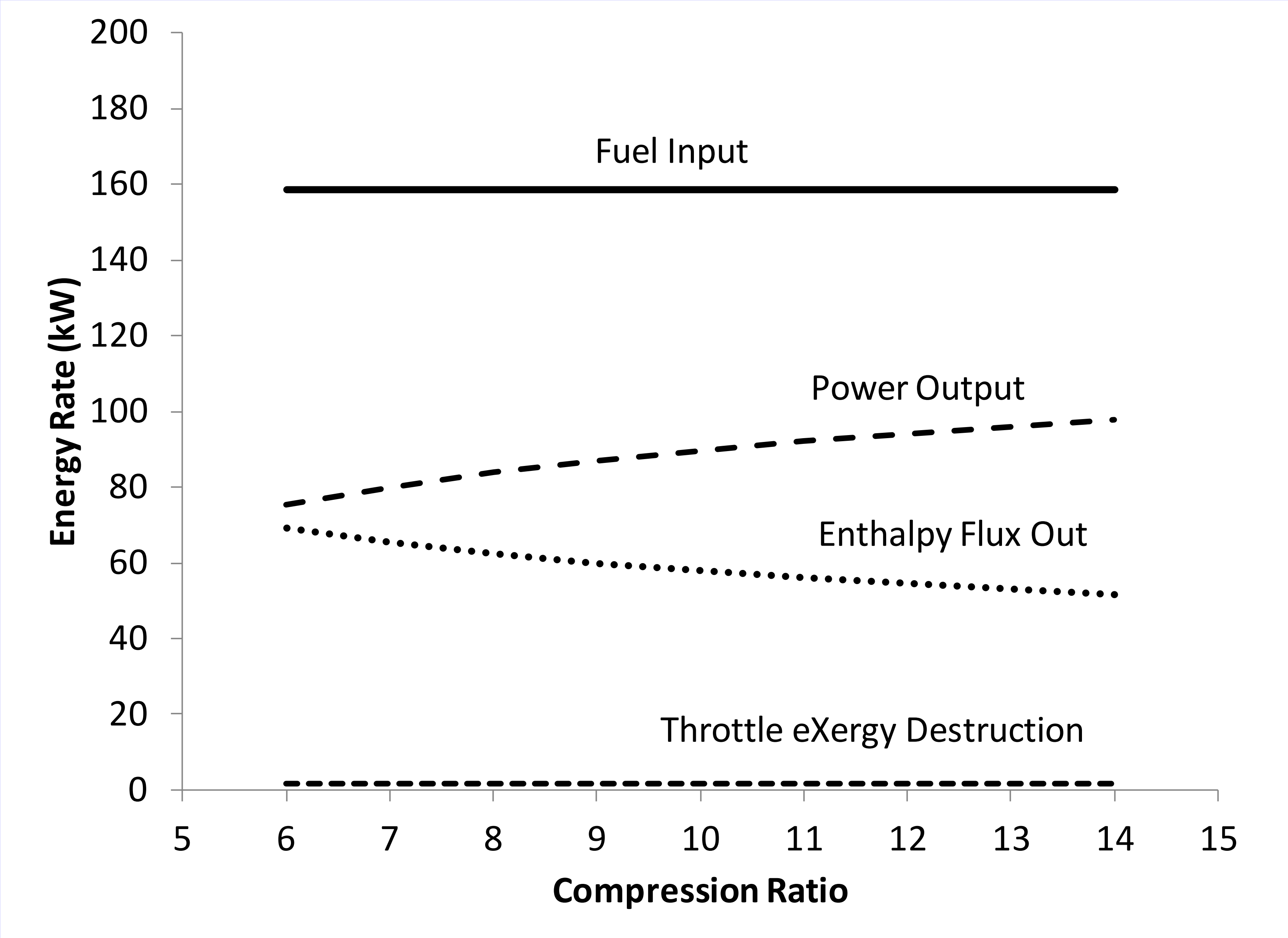
Energy Rate (kW)
250
200
150
100
50
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Intake Runner Pressure (atm)
Fuel Input
Power Output
Enthalpy Flux Out
Throttle eXergy Destruction


Throttle eXergy
Destruction Rate
Exhaust eXergy
Destruction Rate
eXergy Destruction Rate (kW)
Intake Runner Pressure (atm)
0
0.5
1
1.5
2
2.5
3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


Maximum Possible Efficiency = 0.929
2nd Law Efficiency
1st Law Efficiency
Efficiency
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Intake Runner Pressure (atm)

Effect of Compression Ratio




Fuel Input
Power Output
Enthalpy Flux Out
Throttle eXergy Destruction
Energy Rate (kW)
Compression Ratio
200
180
160
140
120
100
80
60
40
20
0
5
6
7
8
9
10
11
12
13
14
15

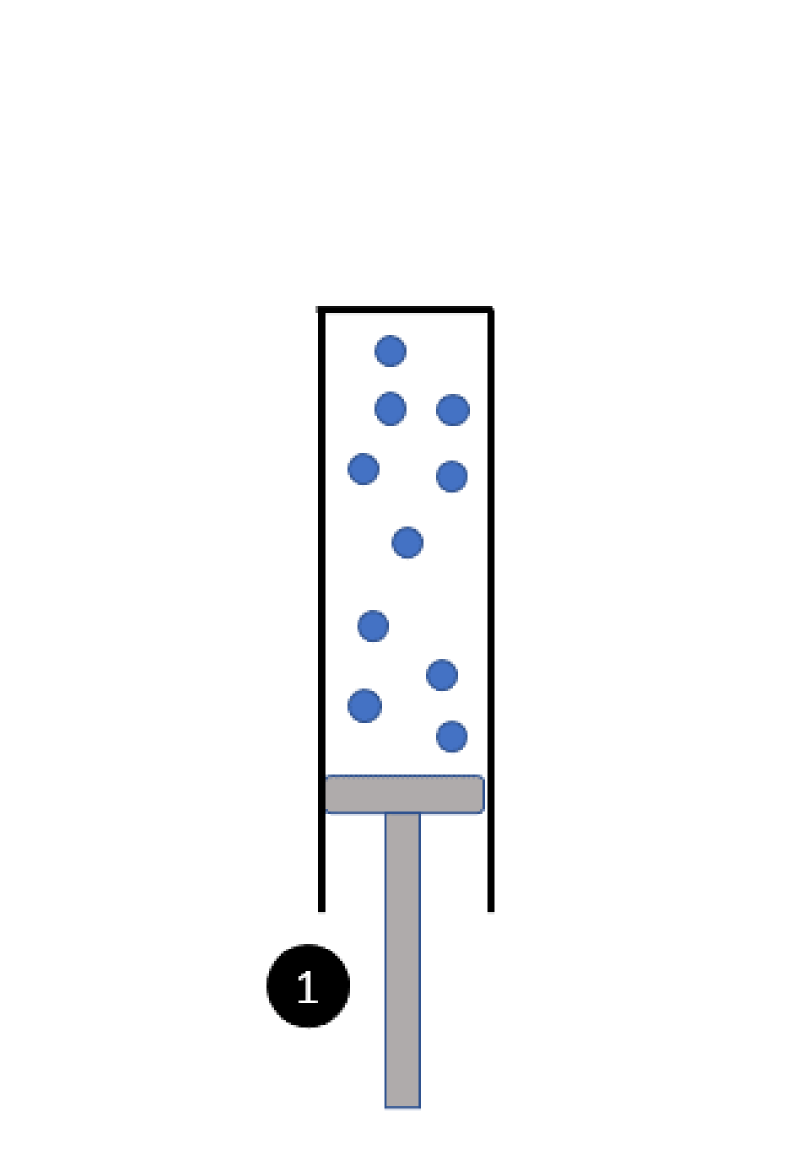
A Mid-Term Quiz from F2020 semester is shown in the next few slides, based on a real issue, namely, the challenge of compressing Martian “air”

COMPRESSING MARTIAN "AIR": The atmosphere of Mars at mid-latitudes can be modeled as consisting of carbon dioxide (CO_2) at a pressure of 0.0078 atm (that's Earth atm) and a temperature of -60^oC. Under those conditions, CO_2 behaves as an ideal gas (due to the low pressure). A NASA team is designing a compressor to fill a receiving tank. (The compressed gas will be subsequently processed chemically to generate O2 for astronauts to breathe, but that is not being analyzed here).

Their first design is a simple piston/cylinder arrangement with 2 check-valves (one at intake to draw Martian air in, one at exhaust to fill the receiving tank). The mechanical cycle starts with the piston at BDC with gas at local Martian atmospheric conditions. The piston is swept completely (so there is no clearance volume). At some intermediate part of the stroke, the pressure will have reached the receiving tank pressure, and the exhaust valve will open (at state 2). Further advance of the piston will push mass into the receiving tank until the cylinder volume is reduced to zero (state 3). Then the piston retracts (the exhaust valve will close and the intake valve will open) and draws in fresh Martian air.

The technology performance goals (see next slide) are a mass flow rate of compressed gas of 12 kg/hour, and an input power per unit mass flow rate less than 1 kW-hr/kg.

The team created a spreadsheet template as a design tool. Default input parameters are listed, and cells that require calculations are highlighted in yellow. The process specifications are listed in the process table. DO NOT ALTER THE STRUCTURE OF THE TEMPLATE AS THIS FILE WILL BE READ FROM ANOTHER PROGRAM. Side calculations can be done below the template, but see if you can put all formulas directly into the cells without doing that. Pay close attention to units.



7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

7.1.2.3 High Pressure-Ratio Gas Compressors

TECHNOLOGY

Technology Description: Mechanically compress atmosphere to higher pressure.

Technology Challenge: Reduced leakage seals between multiple-stage compressors. Flight-weight, yet structurally sound casings for high revolutions per minute (rpm) turbines. Intercoolers that work in low-atmospheric environment (i.e., little convective external cooling).

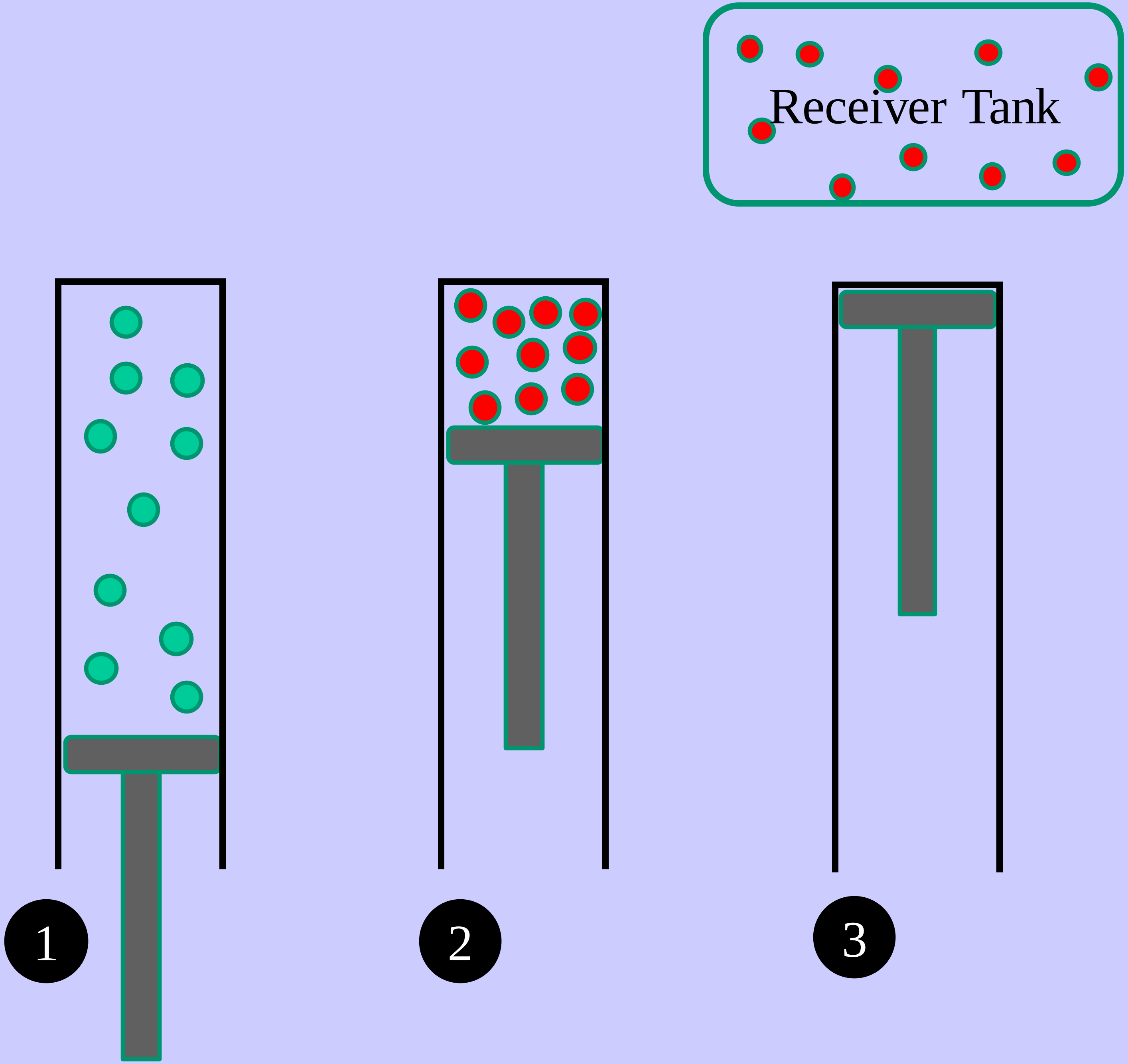
Technology State of the Art: No compressor companies are designing to conditions (compressing 0.8 kPa to ~ 200 kPa).

Parameter, Value:	**TRL**
Very limited testing with off-the-shelf axial blower and custom blower achieving pressure rise < 1.5:1 at low flow rates < 0.12 kilograms of carbon dioxide (CO_2) per hour	3

Technology Performance Goal: Pressure ratio: need to compress low pressure/density resource to reduce volume/mass of downstream reactors and processing components. Efficiency: kW of power / kilogram per hour gas compression. Mass: total mass of production plant needs to be significantly less than mass of propellant produced.

Parameter, Value:	**TRL**
Pressure ratio: > 100:1; Efficiency: < 1 kWe per kilogram per hour of gas compressed; Flow rate: ~ 12 kilograms of CO_2 per hour; Mass: total plant mass < 200 kilograms	6

CAPABILITY	
Needed Capability: Atmospheric resource acquisition and pre-processing.	
Capability Description: Capture, purify, and compress atmospheric gases for processing.	
Capability State of the Art: Closest current capability example is vacuum pump that has flown on Mars Science Lander to evacuate instrument volumes before measurements.	**Capability Performance Goal:** Need to acquire carbon dioxide (CO_2) from the Martian atmosphere at a rate sufficient to produce desired oxygen (O_2) at desired rate. CO_2 rate is dependent on efficiency/ completeness of O_2 production technology (discussed in TA 7.1.3).
Parameter, Value: Pressure reduction: ~ 6 torr down to 1E-6 torr; Flow capacity: not measured	**Parameter, Value:** Rate: 12.1 kilograms of CO_2 per hour to produce 2.2 kilograms of O_2 per hour for Mars crew ascent; Purity: depends on downstream processing method – sabatier, reverse water gas shift, and solid oxide electrolysis might all have different sensitivity to other gases in the feed stream; Pressure: 15 - 40 psia


Receiver Tank
1
2
3

INPUT PARAMETERS

V1	1	liter, maximum cylinder volume
P1	0.0079	atm, ambient pressure
T1	-60	^{o}C, ambient temperature
P2	0.8	atm, pressure of receiving tank
m'	12	kg/hr, target mass flow rate
wtarget	1	kW-hr/kg, target work per unit mass
R	188.9	J/kg/K, gas constant of CO2
cp	846	J/kg/K, enthalpy specific heat of CO2 (assume constant)

DERIVED PARAMETERS

M		kg, mass in cylinder
cv		J/kg/K, internal energy specific heat of CO2
wtarget		kJ/kg, unit conversion of target work/mass

STATE TABLE

state	***V (m^3)***	***P (N/m^2)***	***T (K)***
1			
2			

PROCESS TABLE (all in J)

process	***ΔU***	***Q_{in}***	***W_{out}***	***process specification***
1-2				isentropic compression
2-3	NA			isobaric exhaust
3-1	NA			isobaric intake

RESULTS

w_net		kJ/kg, net work IN per unit mass compressed
N		RPM, required compressor speed
Yes or No?		Does compressor meet target for work per kg?

Combustion 101

Prof. Sidebotham

The Cooper Union for the Advancement of Science and Art

Concepts:

- Fire Triangle
- Flame Types: Premixed vs Diffusion
- Mass Concepts (i.e. Stoichiometry)
- Energy Concepts (i.e. Flame Temperature)

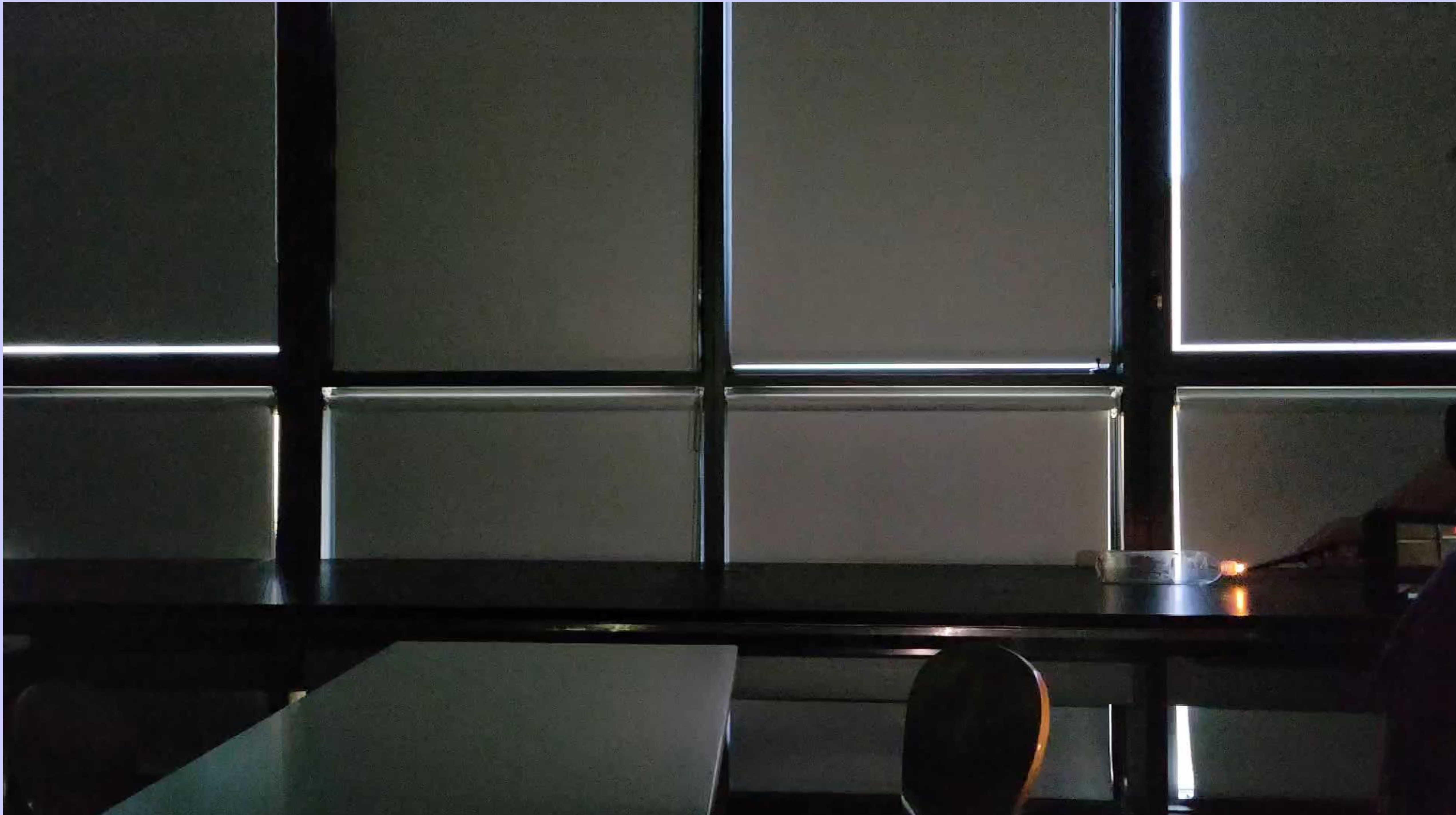
Examples:

- Diffusion Flame Lab (Vlad, Kevin & Dan)
- Isoprocket Demos

On-line Resources:

- JANAF Tables (for properties of chemical species)
- NASA CEA (Chemical Equilibrium Analysis), for calculating detailed equilibrium, like flame temperature.
- CANTERRA (a powerful platform I've dabbled with, and need to speed a lot of time learning how to use).


7°C - 91% isopropyl



Characterizing Diffusion and Premixed Flames in Interchangeable Apparatus

Vlad Bershchanskiy, Kevin Luo, Daniel Zaretsky

Spring 2023

ME360: Engineering Experimentation

Profs. George Sidebotham, David Wootton, Kamau Wright

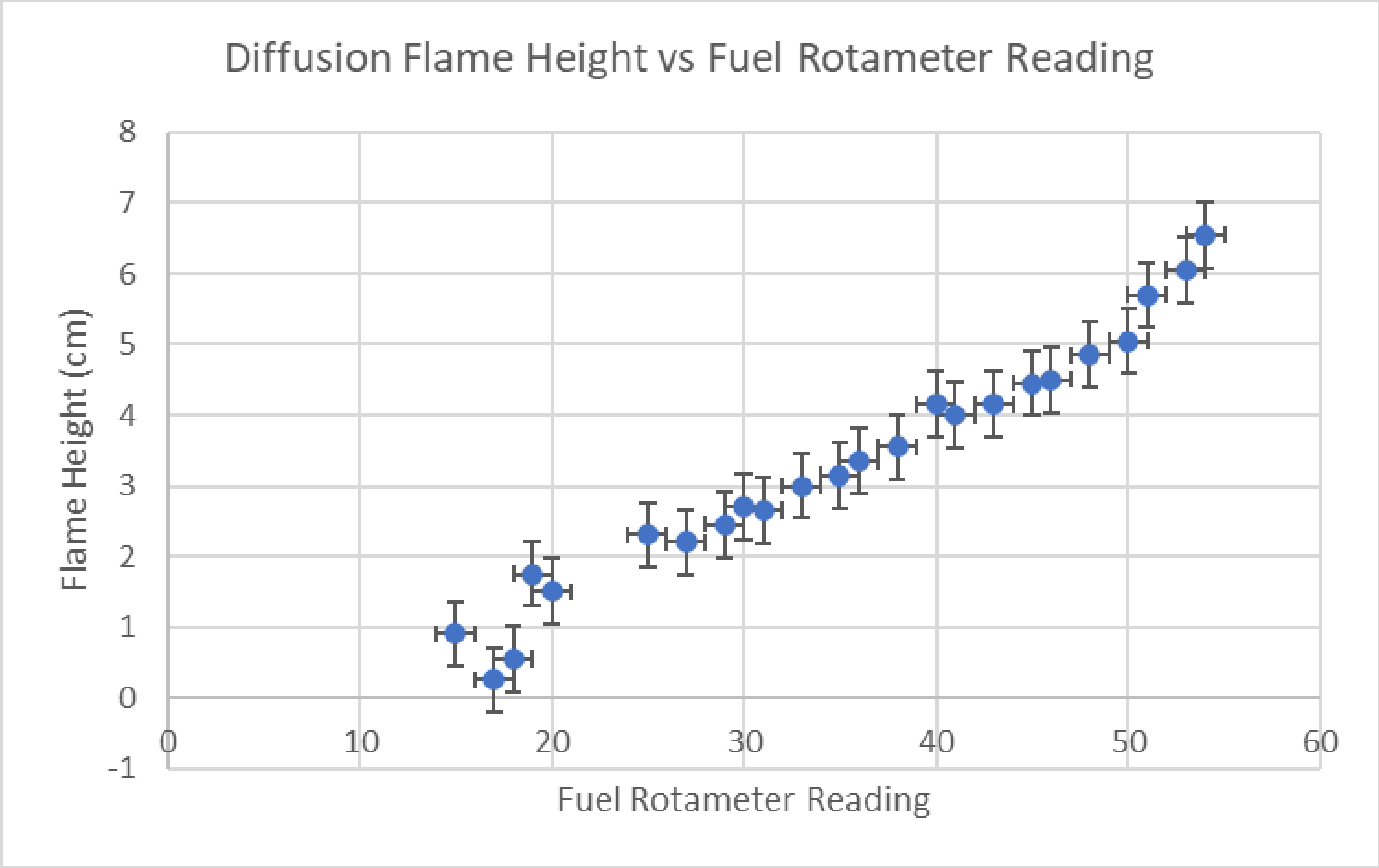
What are Diffusion & Premixed Flames?

- Diffusion Flames are ignited at the fuel/air boundary
- Premixed Flames are ignited mixtures of air and fuel
  - Flashback, when the flame travels down to the fuel source, occurs when fluid velocity becomes slower than the flame speed

Diffusion Flame

Premixed Flame

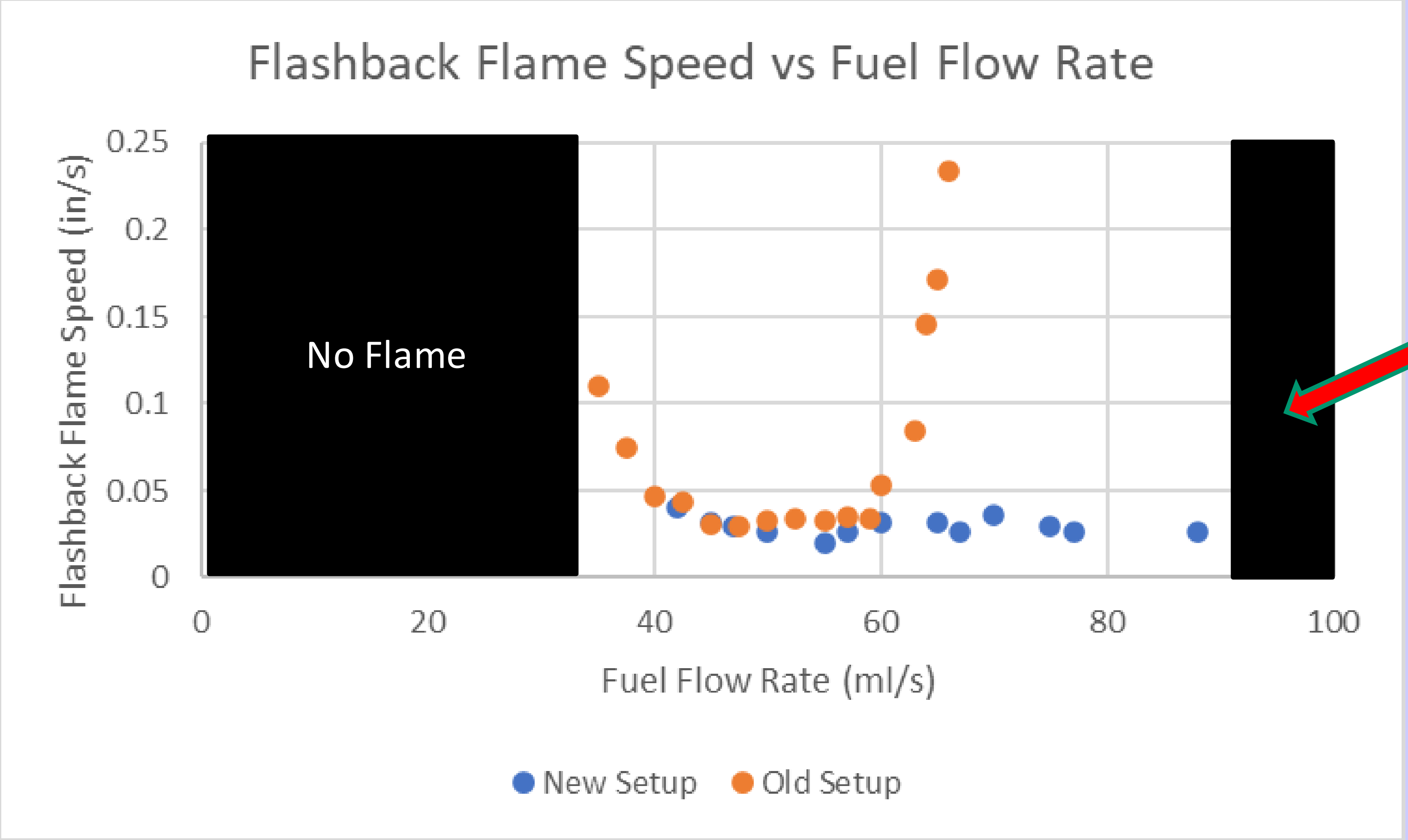
Height vs. Fuel Rotameter Reading



Uncertainty

Flame Height	Fuel Rotameter
± readability of ruler + max difference between readings	± readability of rotameter
± 0.4625 cm	± 1

Results – Flashback Flame Speed



Diffusion Flame
Anchored At Top

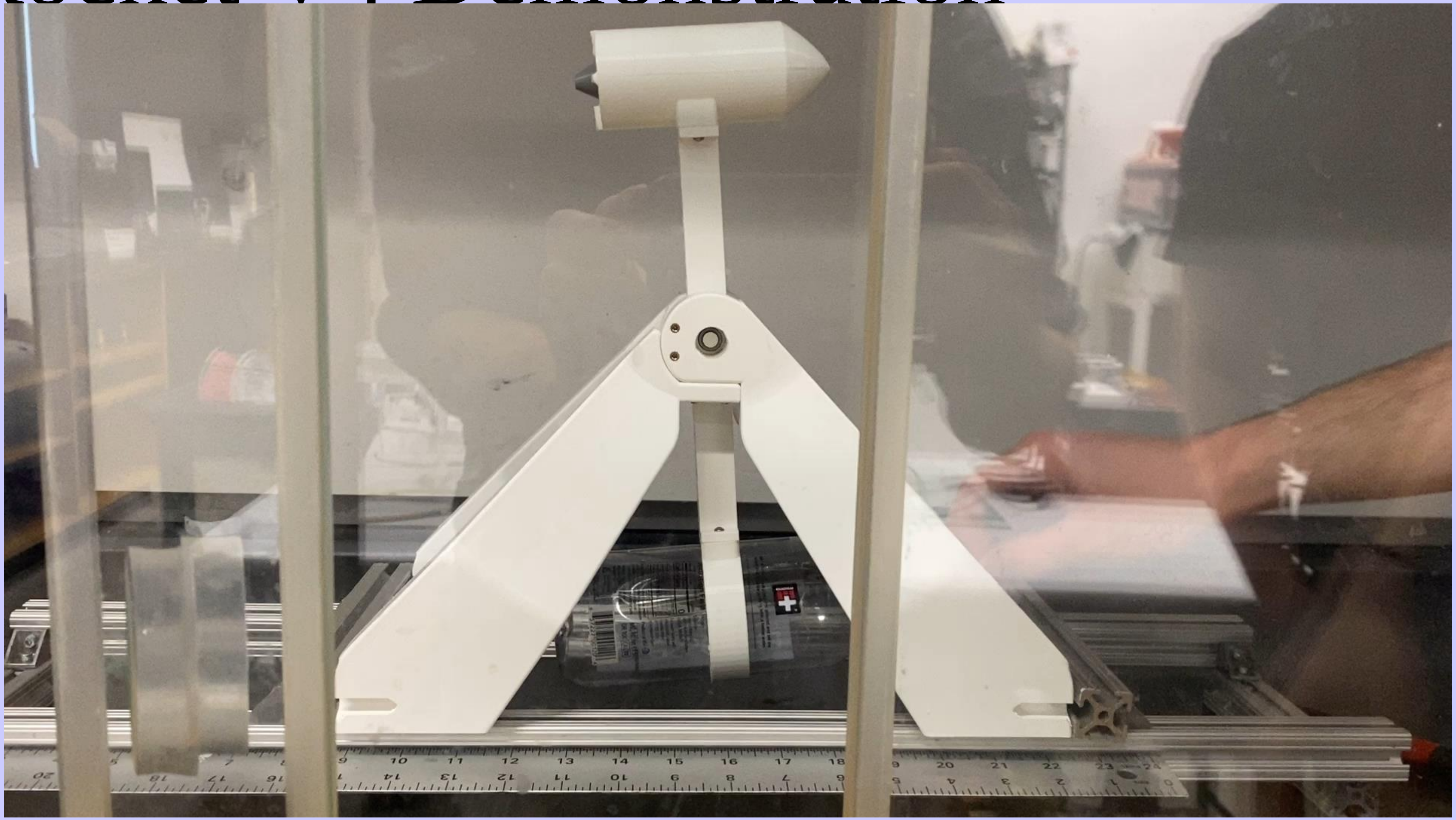
Isoprocket
Impulse Computation using

Ferris Wheel

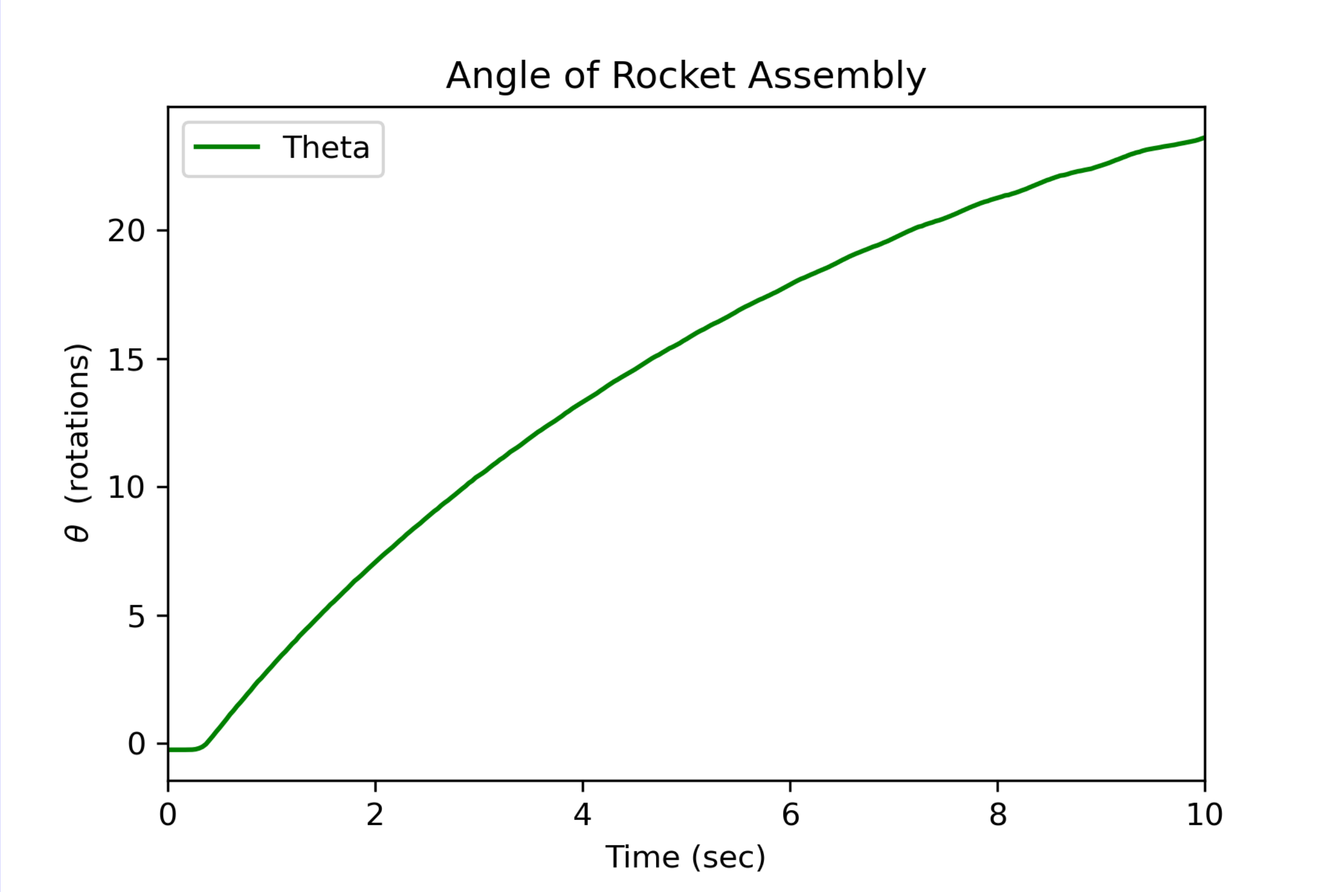
Dynamics

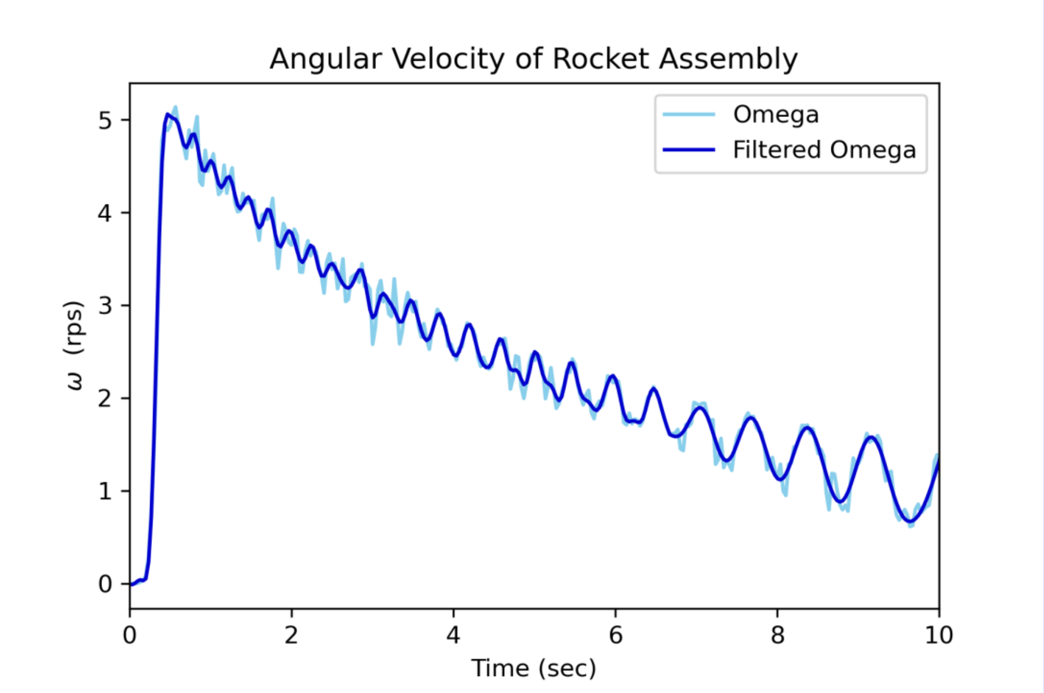
By Team L
Chris Lee
Calder Leppitsch
Alex Landinez

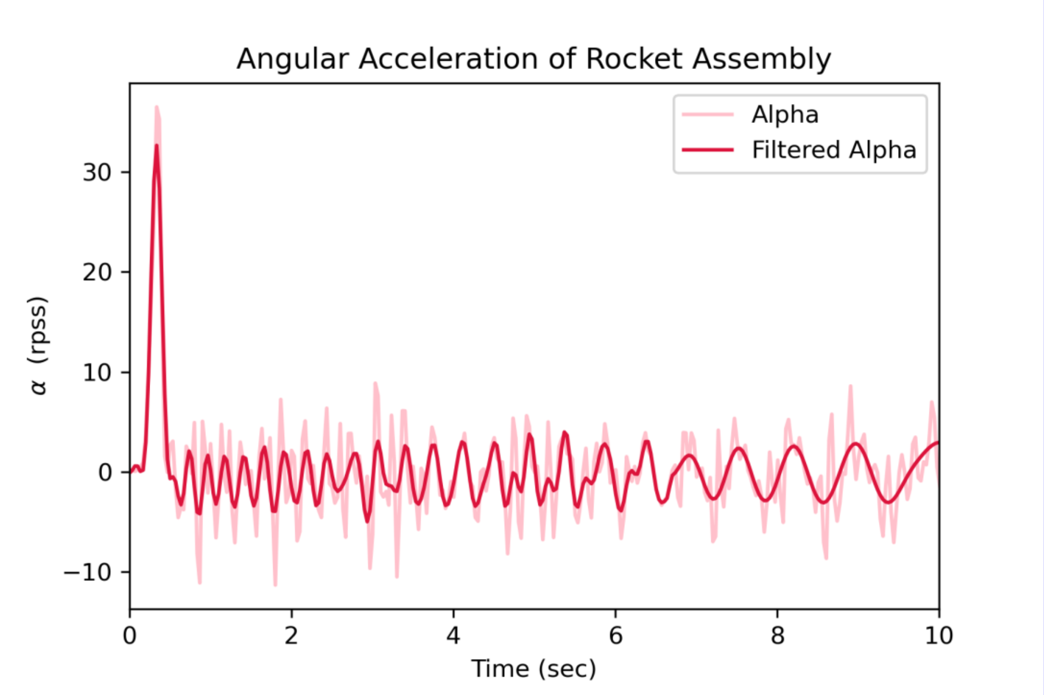
Rocket V4 Demonstration



Tracker Data Processing







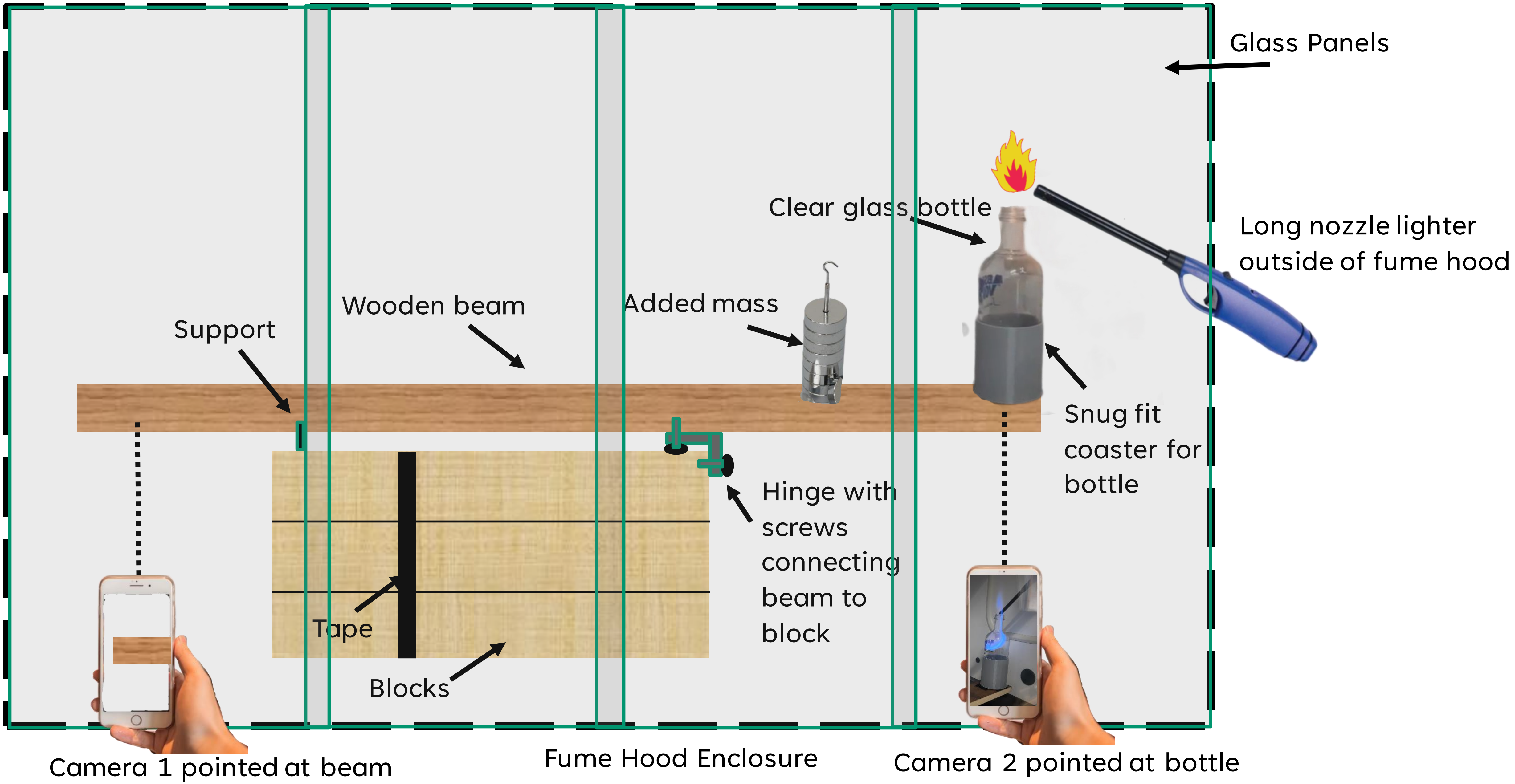
EFFECT OF TEMPERATURE ON FLAME VELOCITY AND THRUST OF AN ISOPROPANOL ROCKET

The Cooper Union for the Advancement of Science and Art

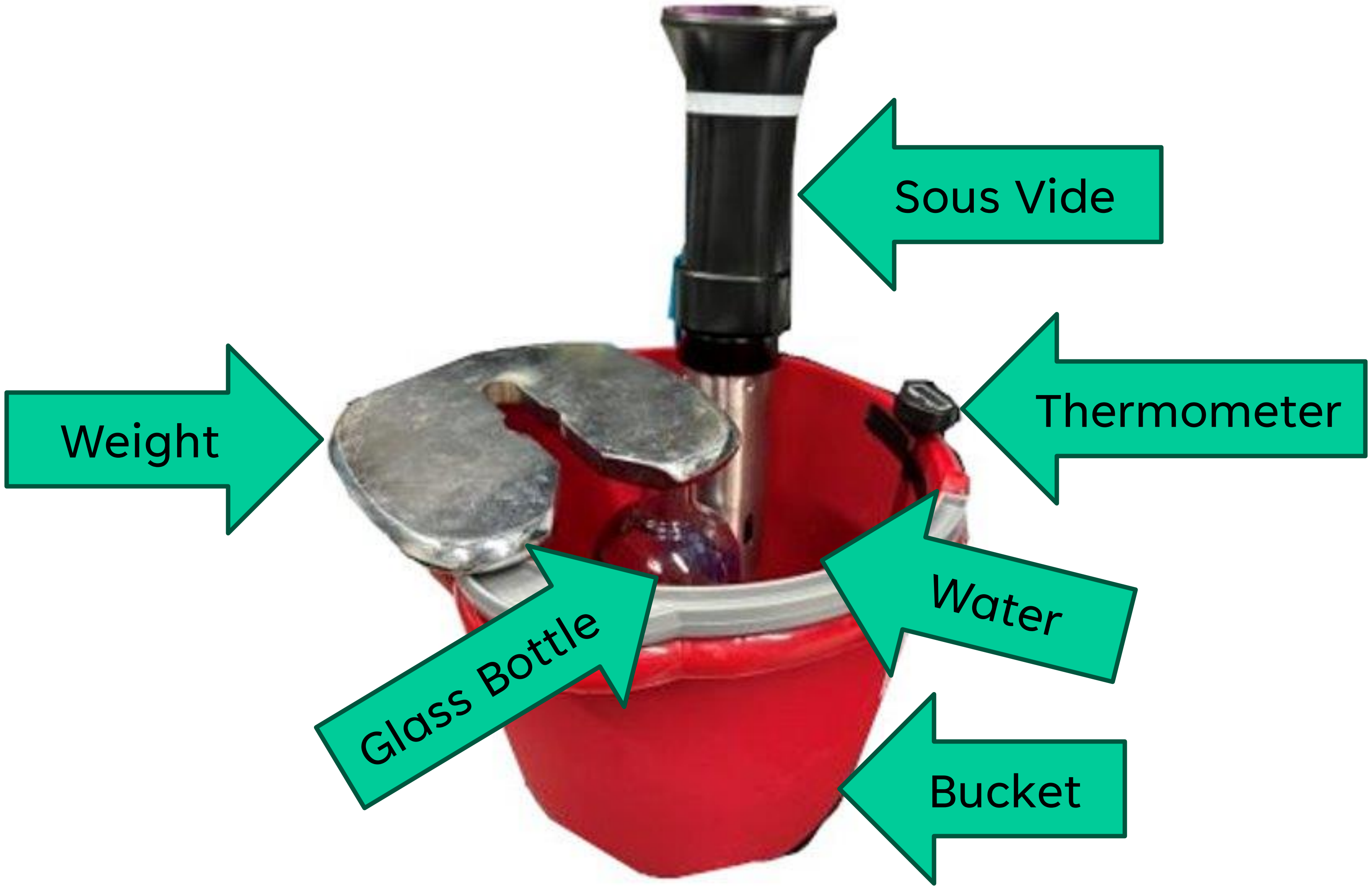
Dr. Wright, Prof. Sidebotham,

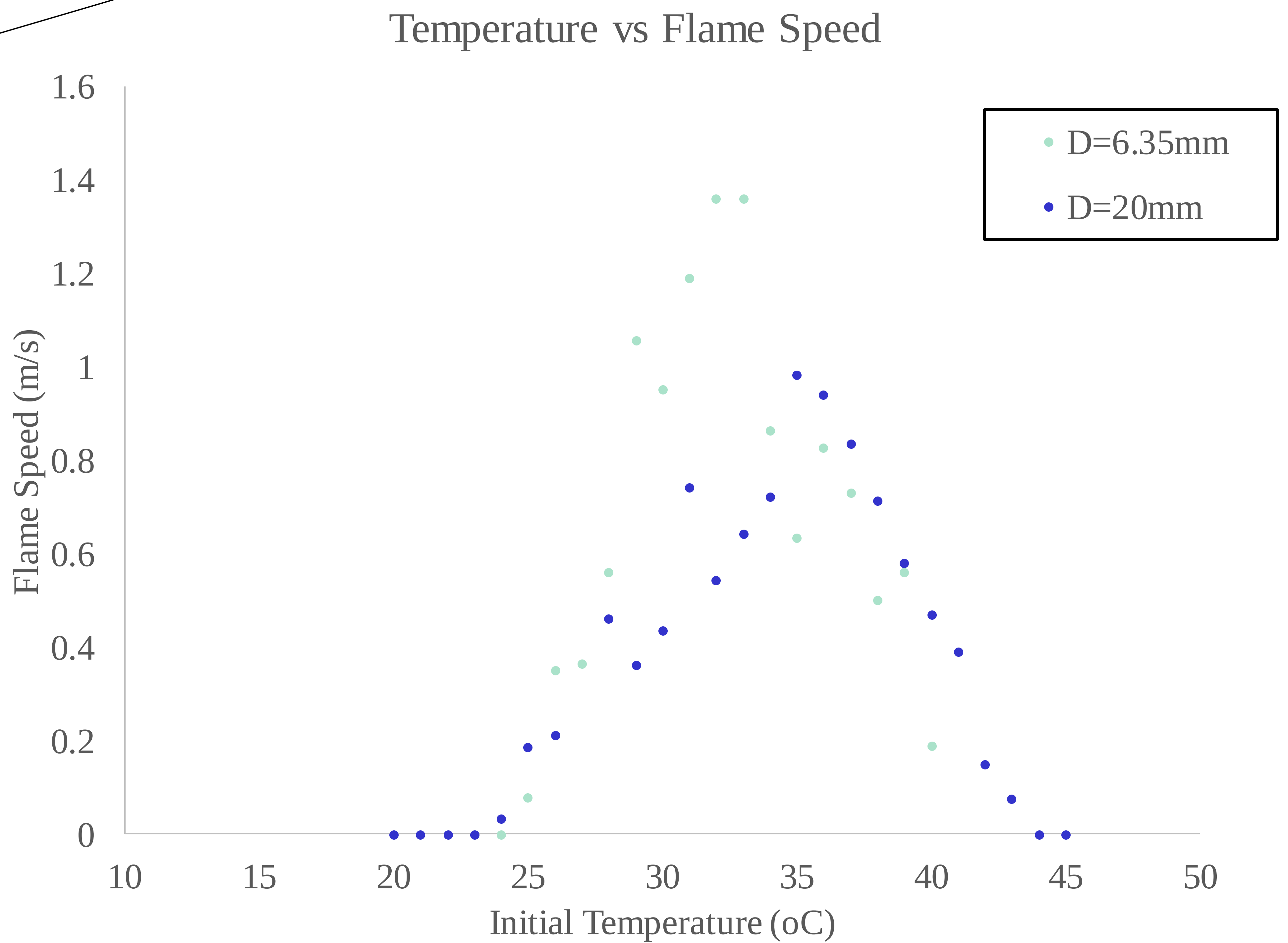
Prof. Wooton

Team C3


Glass Panels
Clear glass bottle
Long nozzle lighter outside of fume hood
Wooden beam
Added mass
Support
Snug fit coaster for bottle
Hinge with screws connecting beam to block
Tape
Blocks
Camera 1 pointed at beam
Fume Hood Enclosure
Camera 2 pointed at bottle

Temperature Control Setup




Temperature vs Flame Speed
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Flame Speed (m/s)
10
15
20
25
30
35
40
45
50
Initial Temperature (oC)
D=6.35mm
D=20mm