Modeling of an Oil-Free Carbon Dioxide Compressor Using Sanderson-Rocker Arm Motion (S-RAM) Mechanism

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Learning Objectives

- Introduction to a CO_2 compressor using a novel driving mechanism
- Introduction to the integrated simulation model

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Outline

- Introduction
- Modeling Effort
  - Kinematics model
  - In-cylinder process model
  - Gas pulsation in discharge pipes
  - Overall energy balance model
- Numerical Methodology
- Simulation Results
- Future Work

Introduction

- High efficiency mechanism to convert shaft rotary motion into piston reciprocating motion.

- Patents

  35+ patents issued since the first patent in 2000

Introduction

- Features
  - Oil free
  - Less frictional power loss
  - Variable capacity control

    (constant clearance volume above the piston top!)

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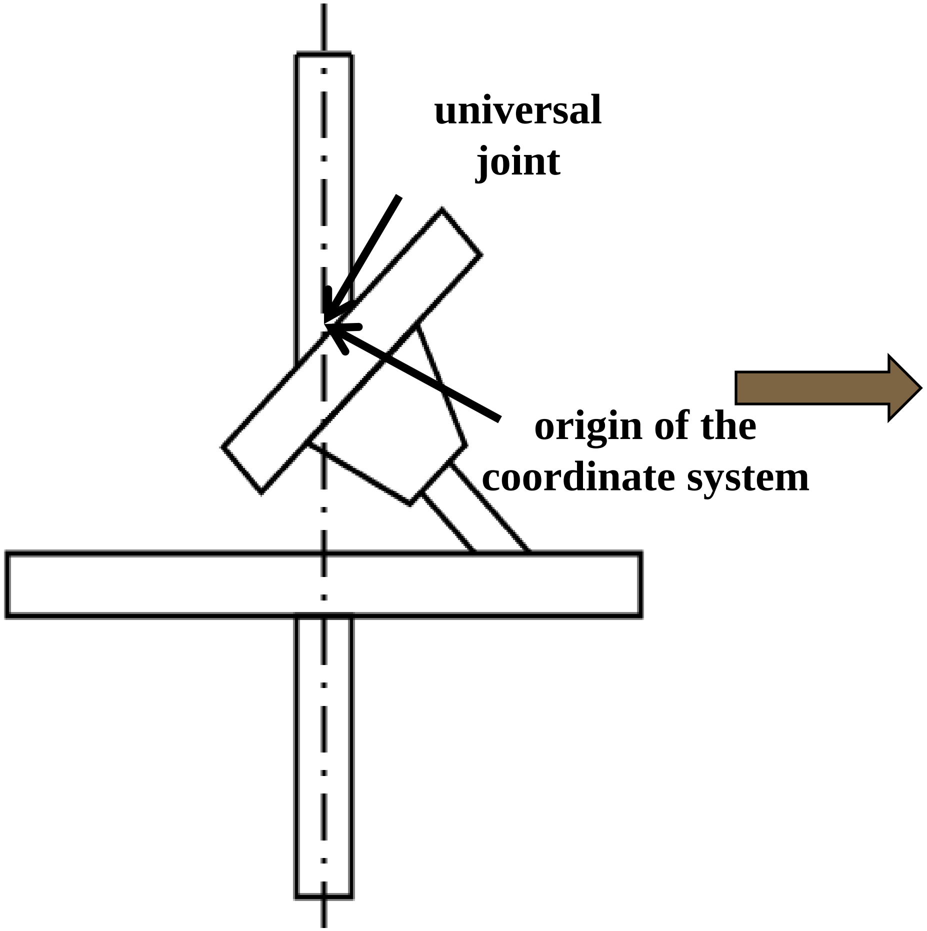
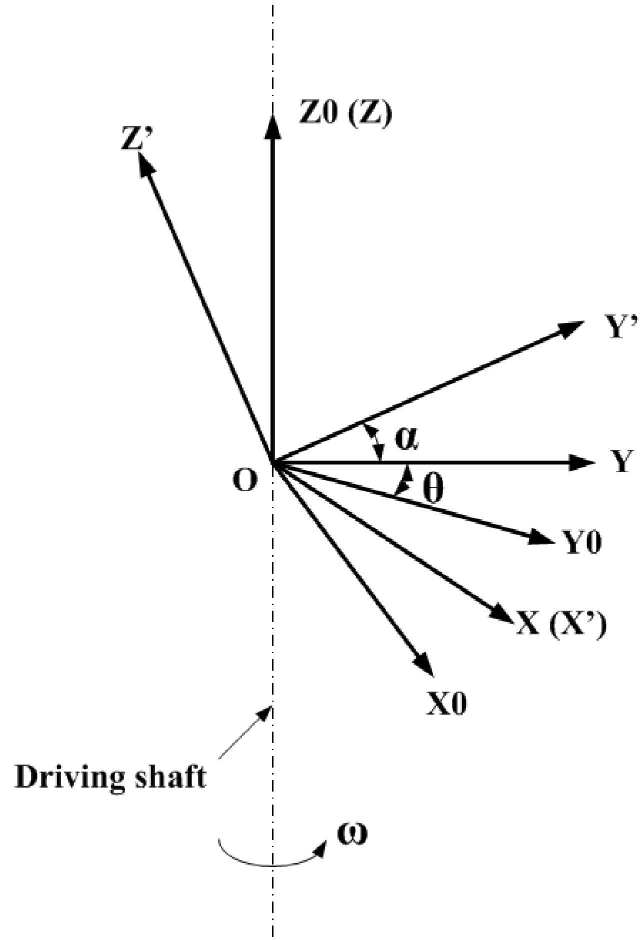
Kinematics Model

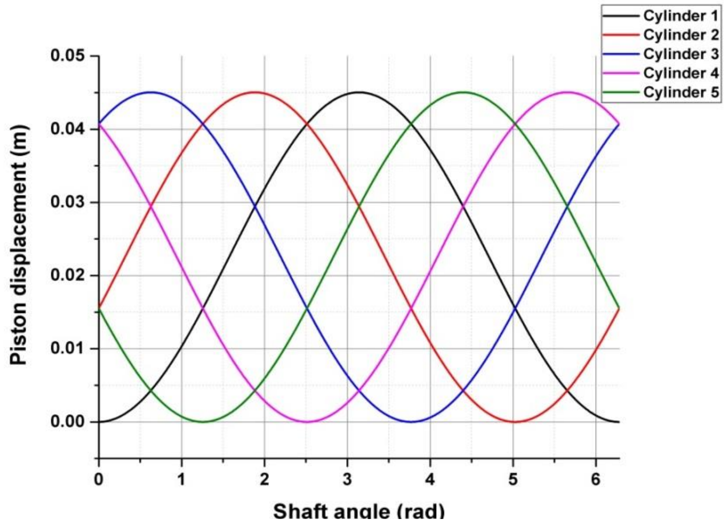


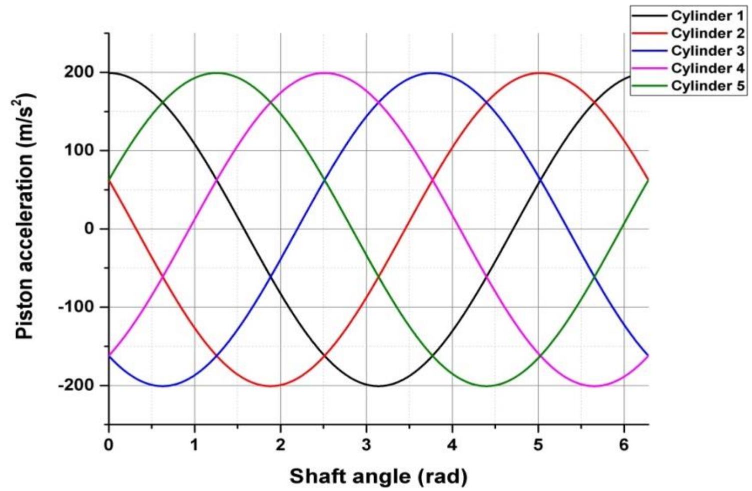
Schematic of Driving Mechanism

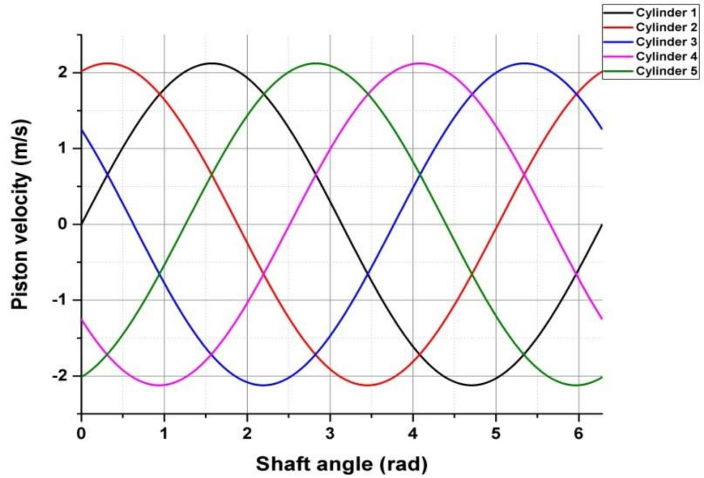


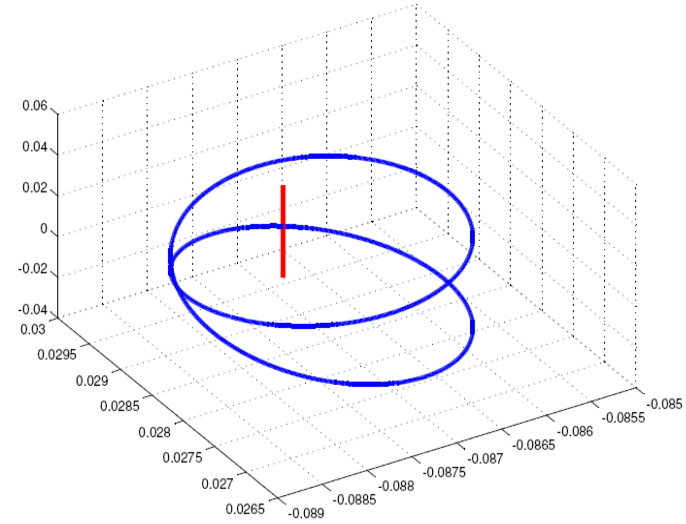
Coordinate System

Kinematics Model

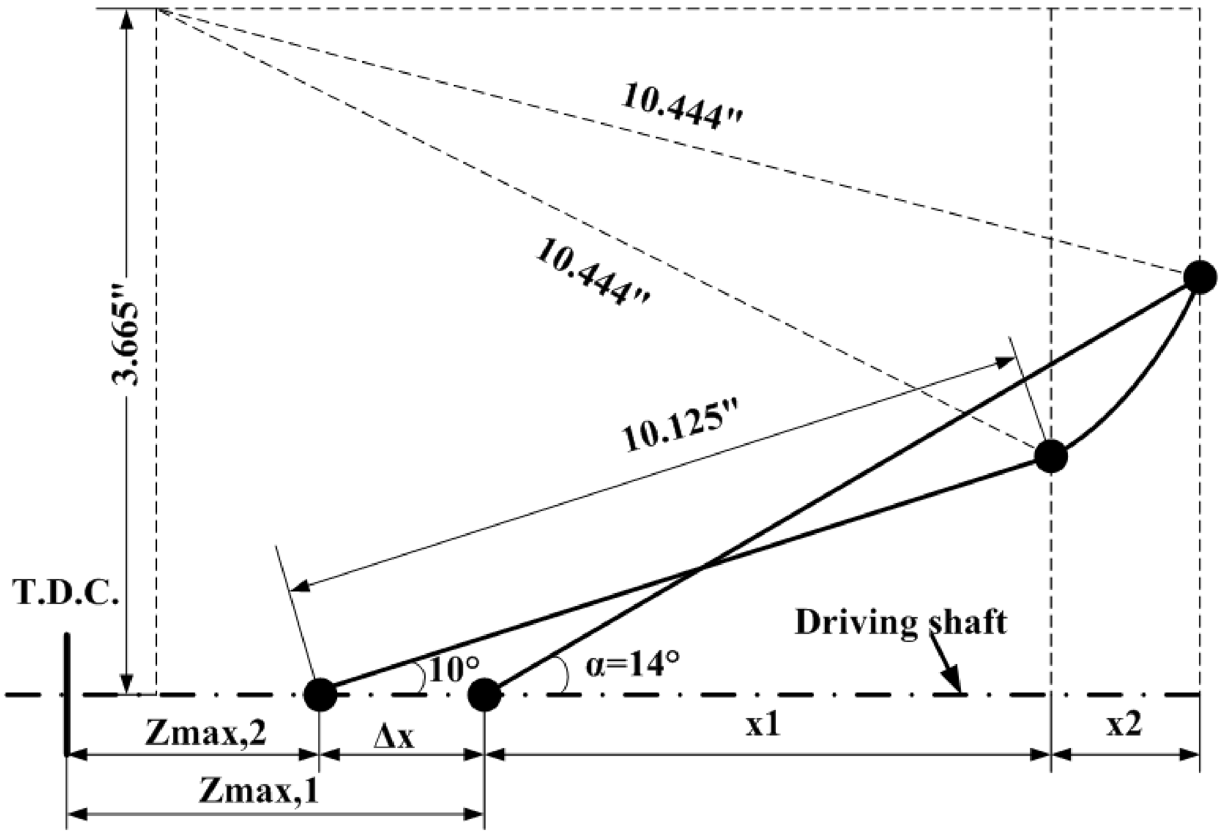








Kinematics Model



$$\alpha = 14^\circ, Z_{\max,1} = 0.044678m$$

$$\alpha = 10^\circ, Z_{\max,2} = 0.0383865m$$

$$Z_{\max,1} = Z_{\max,2} + \Delta x$$

$$\Delta x + x_1 = 10.125 \bullet \cos 10^\circ$$

$$x_1 + x_2 = 10.125 \bullet \cos 14^\circ$$

$$\Delta x = 10.125 \bullet (\cos 10^\circ - \cos 14^\circ) + x_2$$

$$= 0.14693 + 0.10553$$

$$= 0.25246'' = 0.006413\text{m}$$

$$Z_{\max,1} = Z_{\max,2} + \Delta x$$

In-cylinder Process Model

Governing equations

→Continuity equation:

$$\frac{dm_c}{dt} = \frac{dm_{suc}}{dt} + \frac{dm_{li}}{dt} - \frac{dm_{dis}}{dt} - \frac{dm_{lo}}{dt}$$

→Kinematic equation:

$$\frac{dv_c}{dt} = \frac{1}{m_c}\frac{dV_c}{dt} - \frac{V_c}{m_c^2}\frac{dm_c}{dt}$$

→Energy equation:

$$\frac{dQ}{dt} + \frac{dW}{dt} = \frac{d(m_c u_c)}{dt} + \frac{dm_{dis}}{dt}h_{dis} + \frac{dm_{lo}}{dt}h_{lo} - \frac{dm_{suc}}{dt}h_{suc} - \frac{dm_{li}}{dt}h_{li}$$

Leakage model: isentropic, compressible fluid

$$\begin{cases} \dot{m}_{gap} = \dfrac{dm_{gap}}{dt} = C_{gap}A_{gap}p_u\left(\dfrac{2}{ZRT_u}\right)^{\frac{1}{2}}\left\{\dfrac{\kappa}{\kappa-1}\left[\left(\dfrac{p_d}{p_u}\right)^{\frac{2}{\kappa}} - \left(\dfrac{p_d}{p_u}\right)^{\frac{\kappa+1}{\kappa}}\right]\right\}^{\frac{1}{2}}, \dfrac{p_d}{p_u} > 0.54 \\ \dot{m}_{gap} = \dfrac{dm_{gap}}{dt} = C_{gap}A_{gap}p_u\left(\dfrac{\kappa}{ZRT_u}\right)^{\frac{1}{2}}\left[\left(\dfrac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}\right]^{\frac{1}{2}}, \dfrac{p_d}{p_u} \le 0.54, choked \end{cases}$$

Valve model: isentropic, compressible fluid

$$\dot{m}_{valve} = \frac{dm_{valve}}{dt} = C_{valve}A_{valve}(2\rho_{high}p_{high})^{\frac{1}{2}}\left\{\frac{\kappa}{\kappa-1}\left[\left(\frac{p_{low}}{p_{high}}\right)^{\frac{2}{\kappa}} - \left(\frac{p_{low}}{p_{high}}\right)^{\frac{\kappa+1}{\kappa}}\right]\right\}^{\frac{1}{2}}$$

Gas Pulsation in Discharge Pipes

- Anechoic assumption
- Elson and Soedel's method (1974)

$$Z = \frac{p_{pul}}{u_{pul}} = \rho_0 c$$

impedance

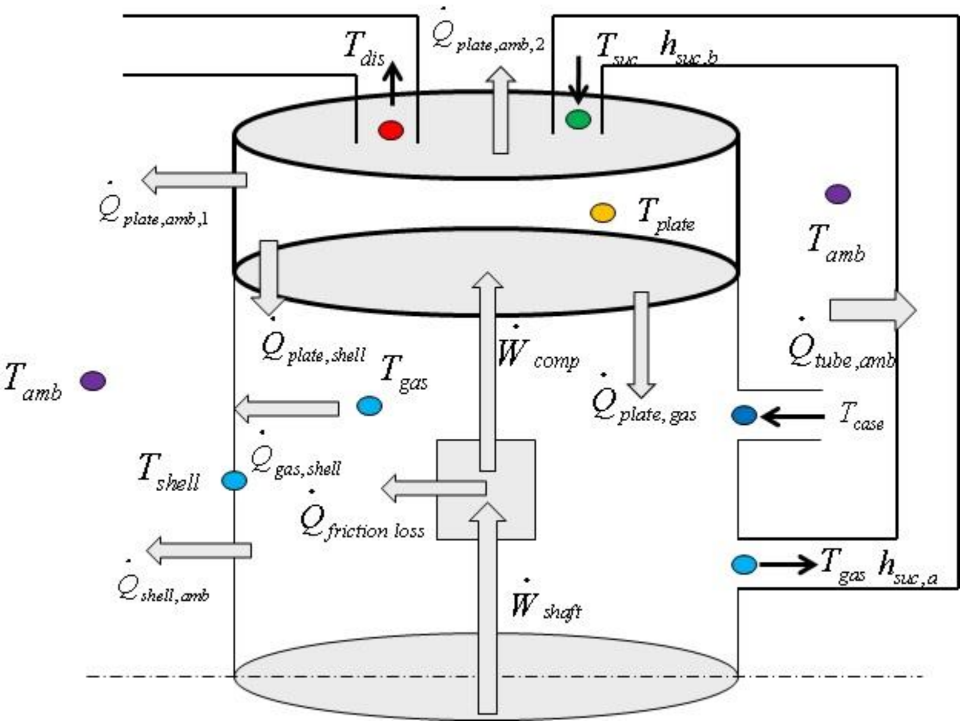
oscillated acoustic pressure

gas density in the pipeline

gas velocity

speed of sound

Overall Energy Balance Model



Schematic of overall energy flow

$$\dot{m}_{comp}(h_{suc,a}-h_{case})=\dot{Q}_{plate,gas}-\dot{Q}_{gas,shell}+\dot{Q}_{friction,loss}$$

$$\dot{Q}_{gas,shell}-\dot{Q}_{shell,amb}=0$$

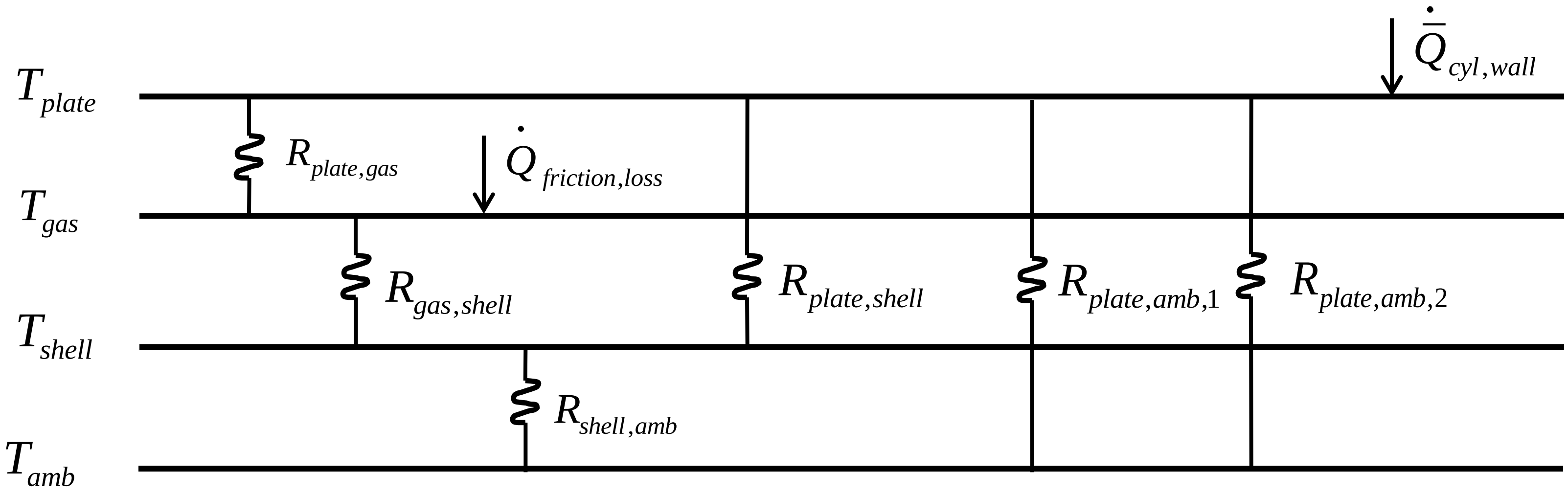
$$-\dot{Q}_{plate,amb,1}-\dot{Q}_{plate,amb,2}-\dot{Q}_{plate,gas}-\dot{\bar{Q}}_{cyl,wall}=0$$

$$\dot{Q}_{pipe,amb}+\dot{m}_{comp}(h_{suc,a}-h_{suc,b})=0$$

$$\dot{W}_{comp}+\dot{\bar{Q}}_{cyl,wall}=\dot{m}_{comp}(h_{dis}-h_{suc,b})$$

$$\dot{Q}=\frac{T_a-T_b}{R_{ab}}$$

Overall Energy Balance Model



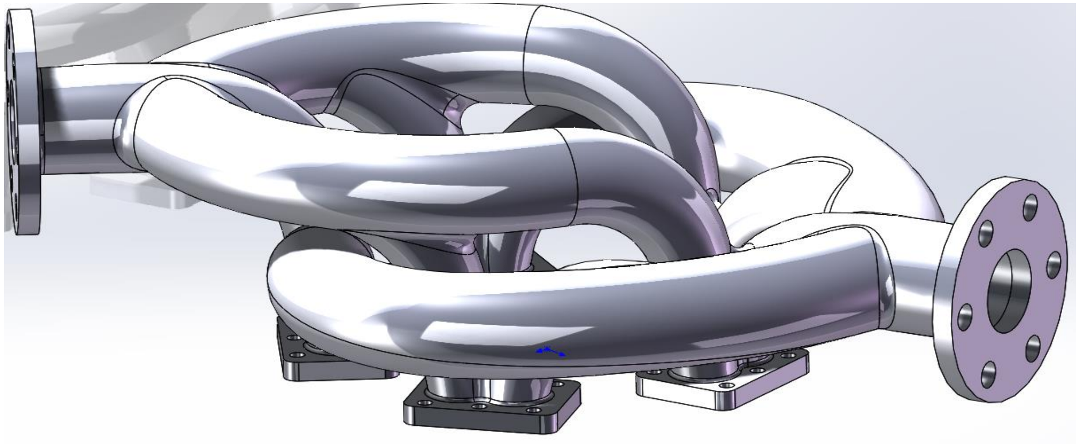
Thermal resistance network of the overall energy balance

$$\dot{\bar{Q}}_{cyl,wall} = \frac{n}{60}\int_{t}^{t+\Delta T} \dot{Q}_{cyl,wall}\, dt$$

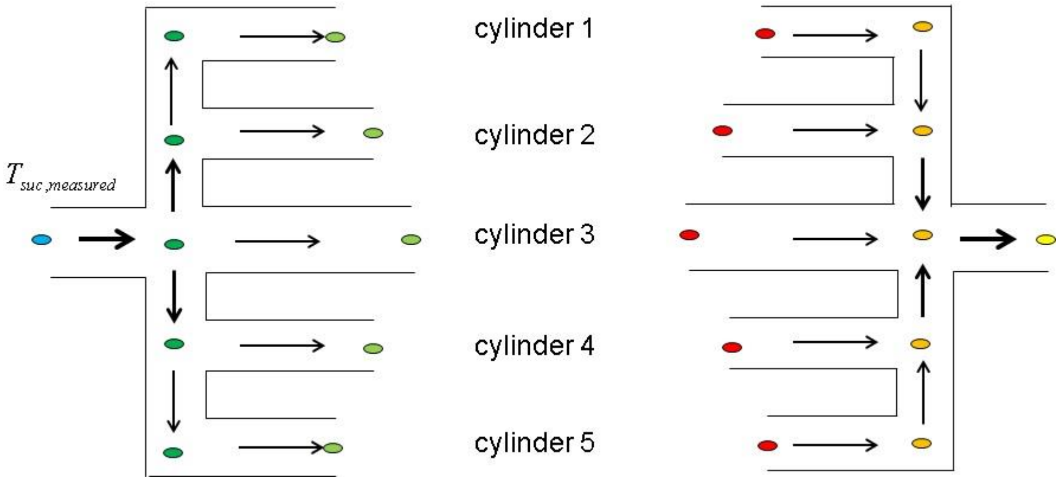
Overall Energy Balance Model

- Heat transfer categories:
  - Convection along the horizontal plate
  - Convection along the vertical plate
  - Convection along the horizontal pipe
  - Convection along the vertical pipe
  - Heat conduction between cylinder plate and case shell (neglected here)

Overall Energy Balance Model



Real pipe arrangement



Simplified pipe arrangement

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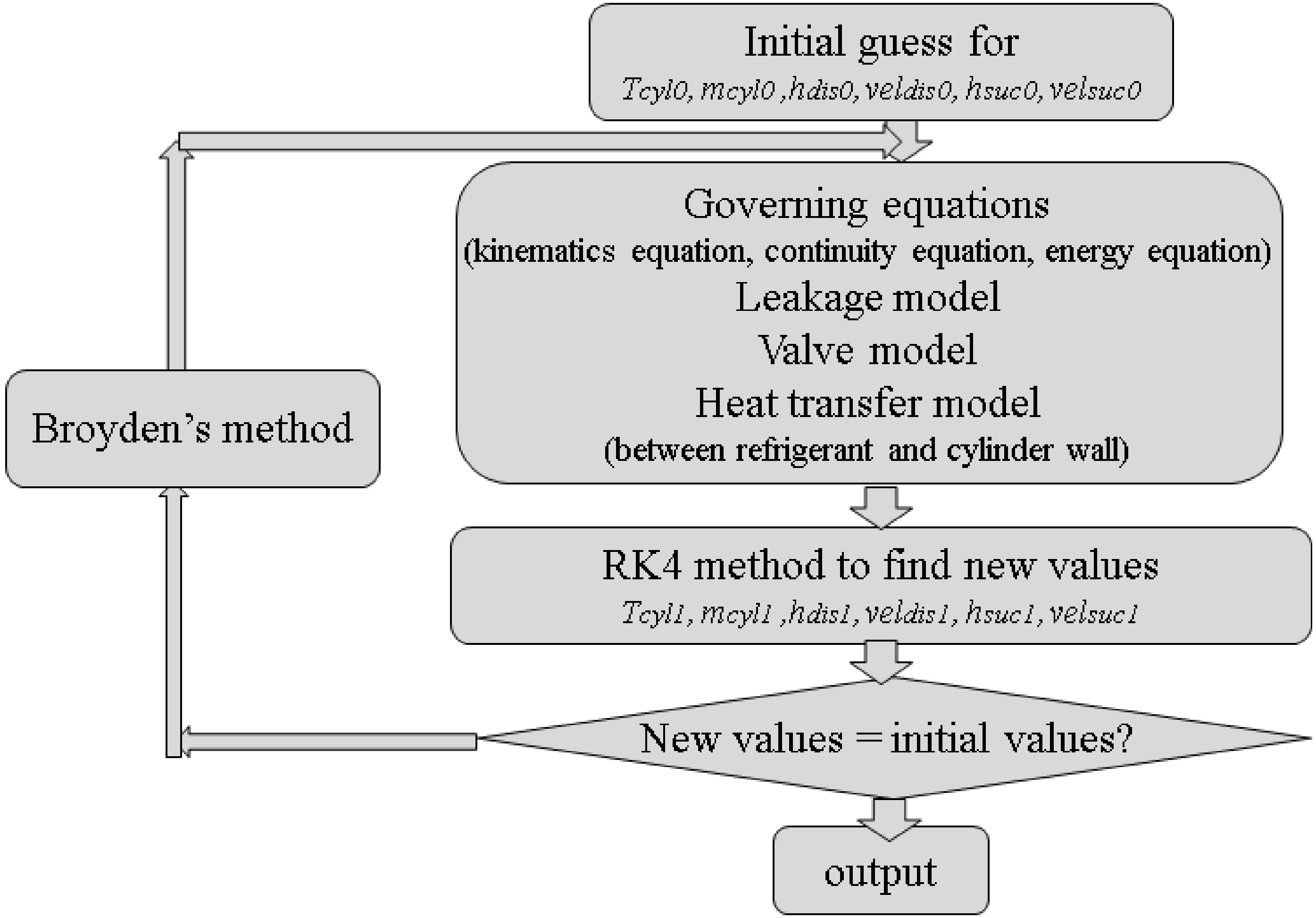
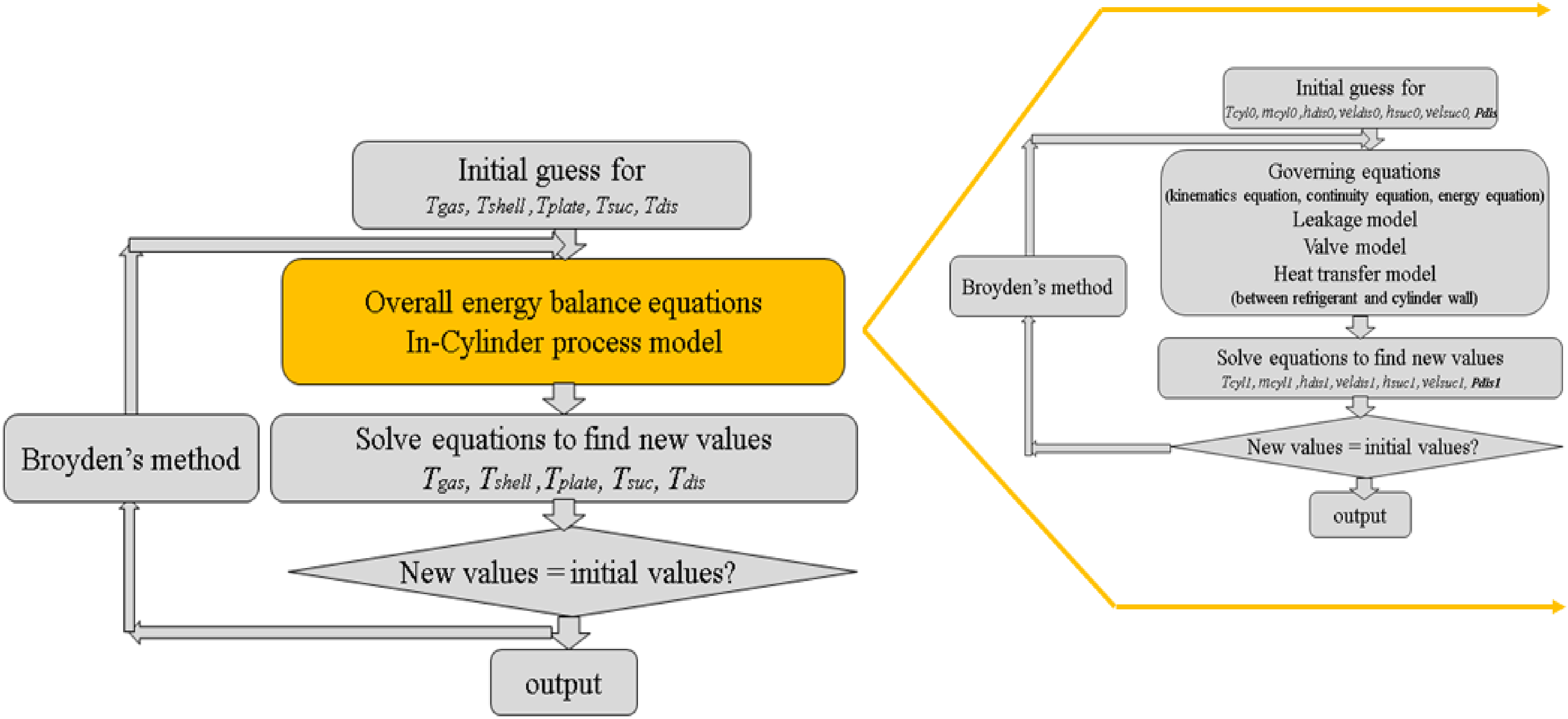
Numerical Methodology



Flow chart of in-cylinder process model solution

Numerical Methodology



Flow chart of overall compressor model solution

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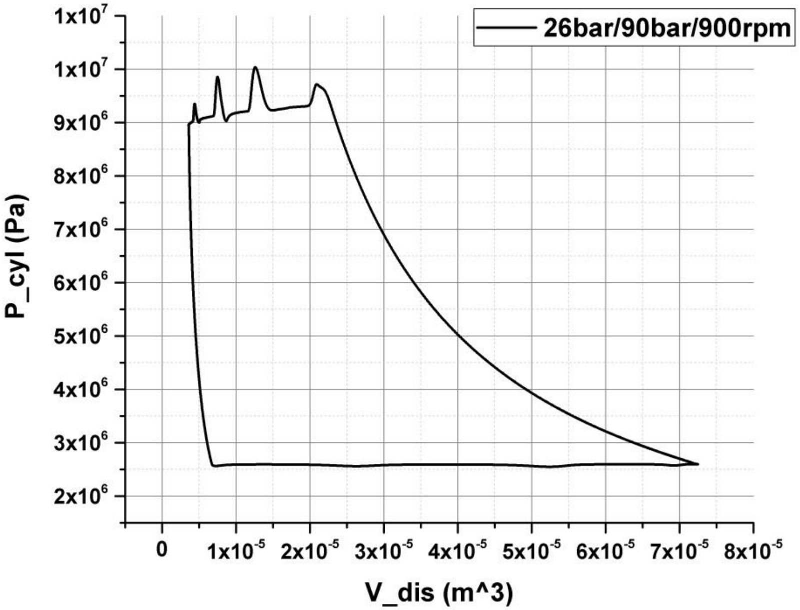
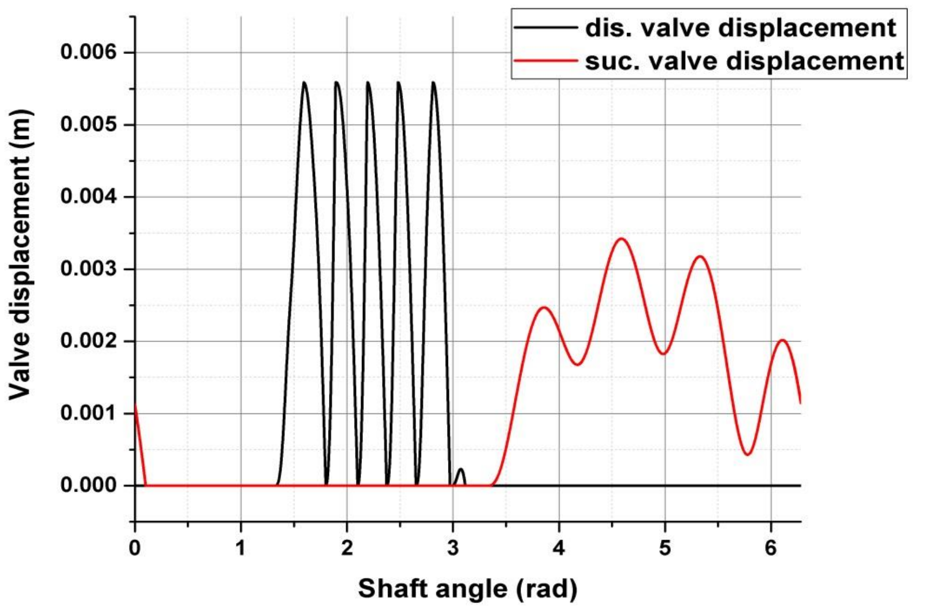
Simulation Results



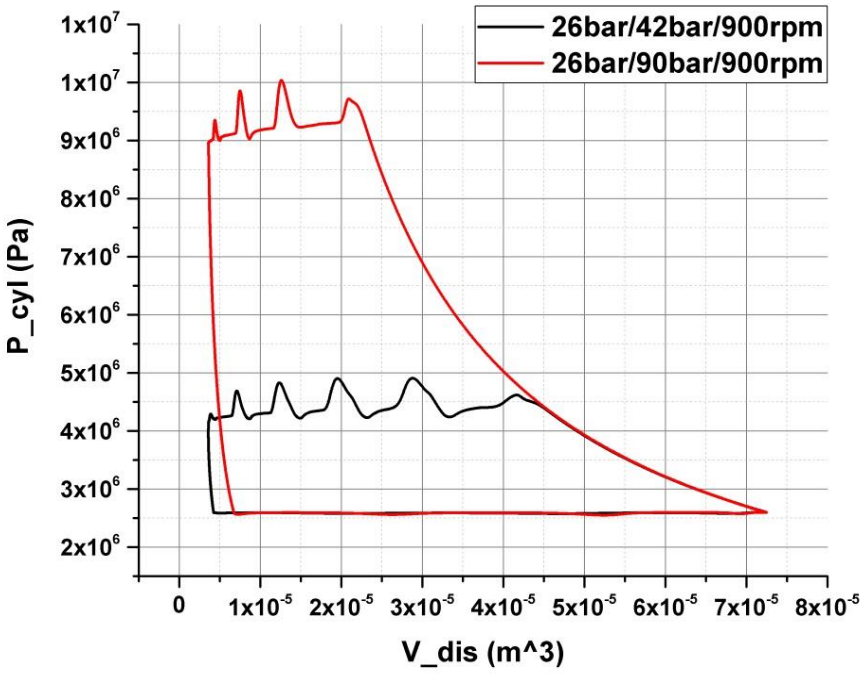
P-V diagram



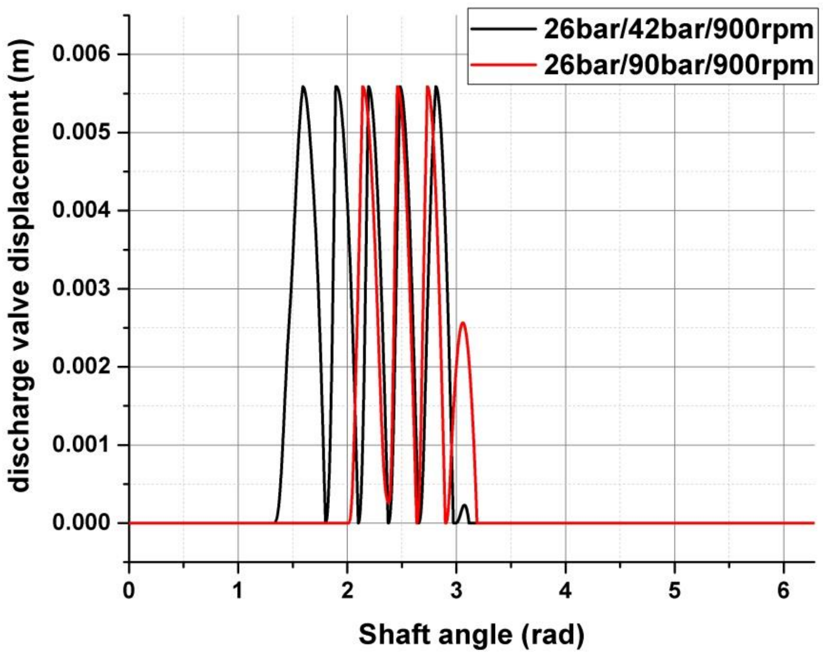
Valve displacement

Simulation Results

- Effect of discharge pressure



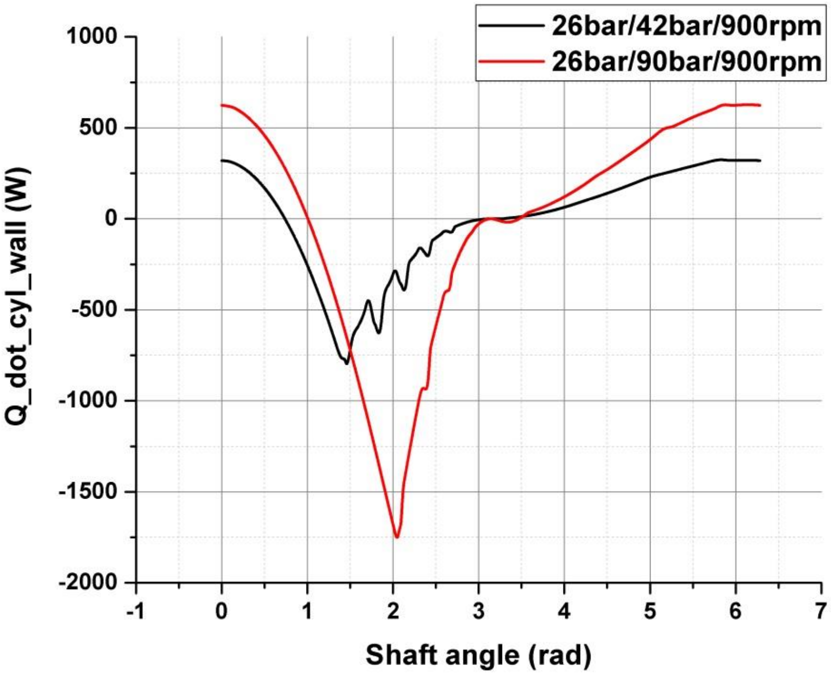
P-V diagram



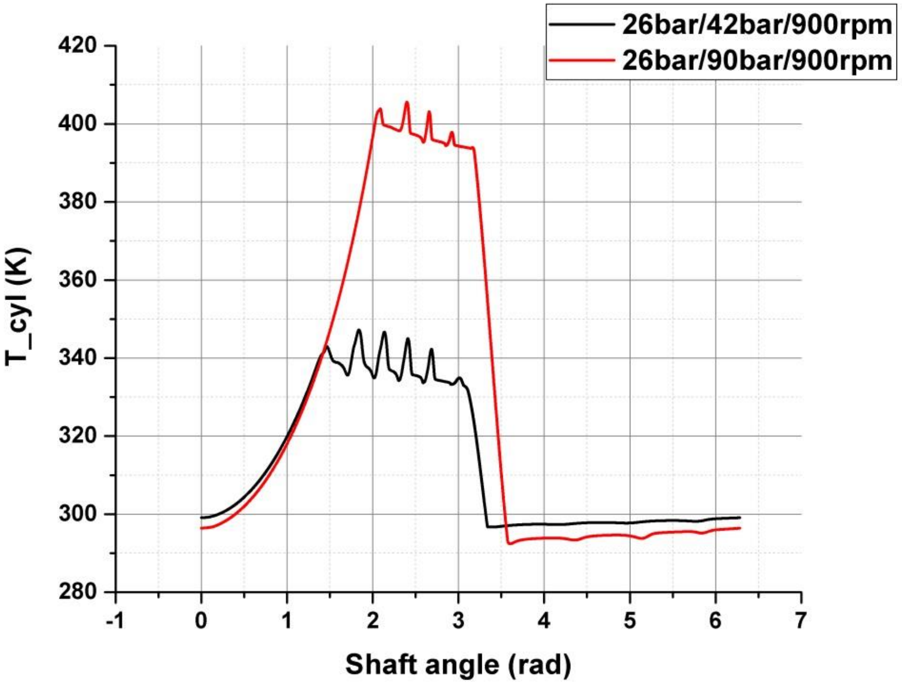
Discharge valve displacement

Simulation Results

➢ Effect of discharge pressure



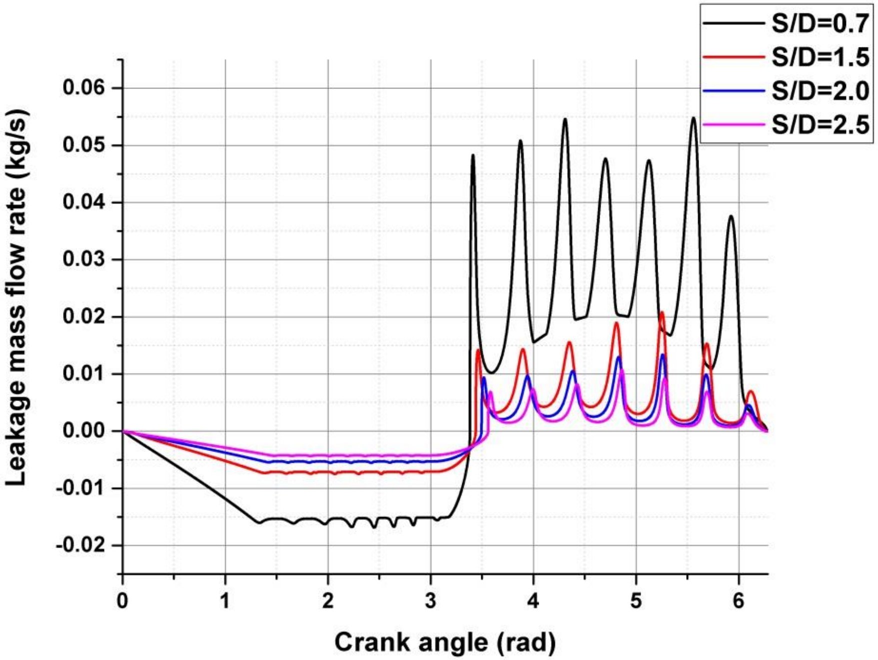
Instantaneous heat transfer between in-cylinder refrigerant and cylinder wall



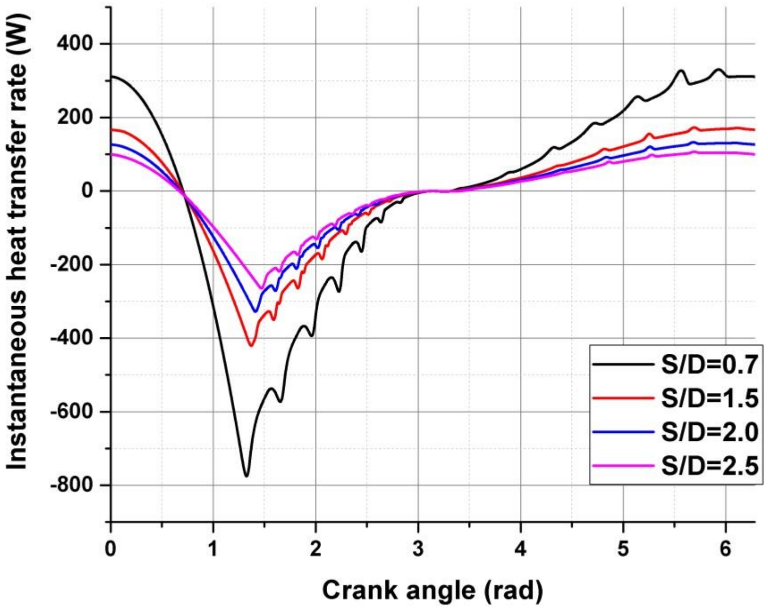
In-cylinder refrigerant temperature

Simulation Results

- Effect of stroke-to-bore ratio



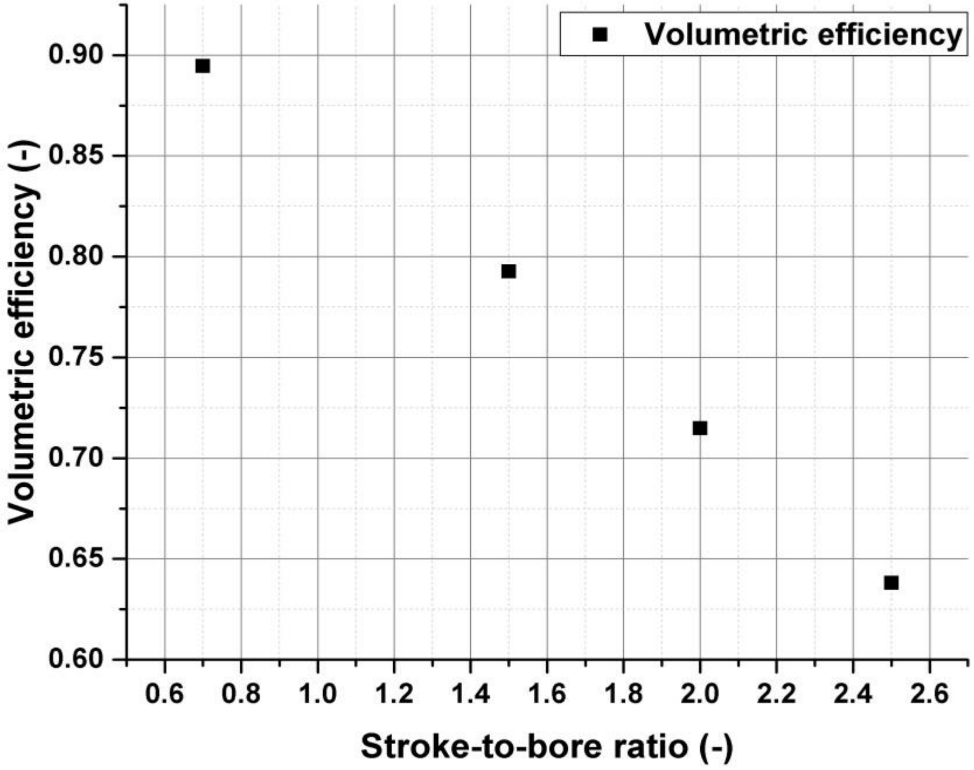
Instantaneous refrigerant leakage through clearance between piston assembly and cylinder wall



Instantaneous heat transfer between in-cylinder refrigerant and cylinder wall

Simulation Results

- Effect of stroke-to-bore ratio



Effect of stroke-to-bore ratio on the volumetric efficiency

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Future Work

- Dynamics model (frictional power loss)
- Performance testing of the prototype compressor
- Discharge pipe gas pulsation measurement
- Validation of the simulation model
- Parametric studies

Questions?

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