# Simulation Study on the Performance of an Injection Scroll Compressor in a Heat Pump for Electric Vehicles

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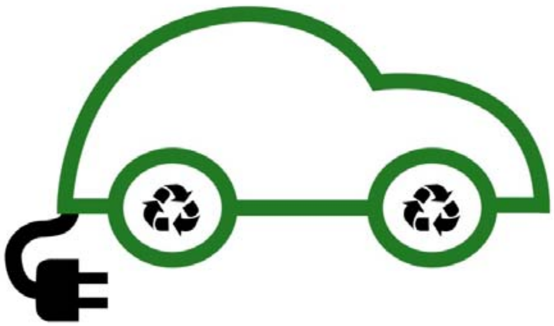
# Introduction

## Background

- **Electric vehicles**



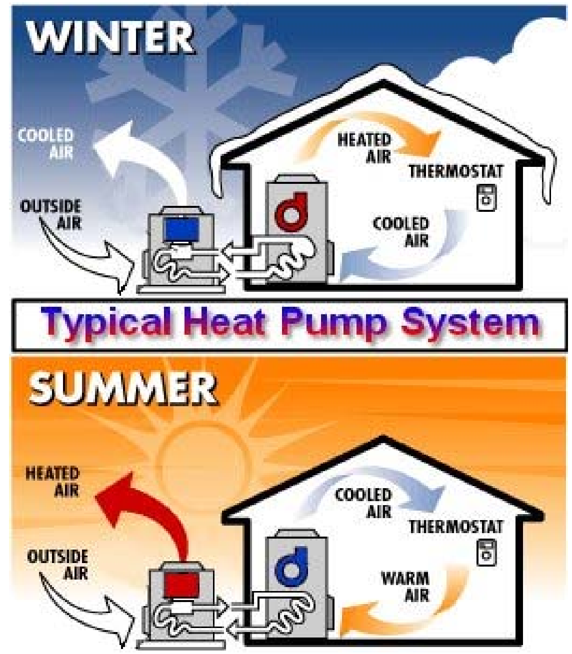
Eco-friendly and energy efficient road transportation.

Driving distance per charge : about 130~160 km (only suitable for city trips and other short hauls)

HVAC system impacts its power consumption and driving range.

**Winter 30%, Summer 20%**

- **Heat pump system**

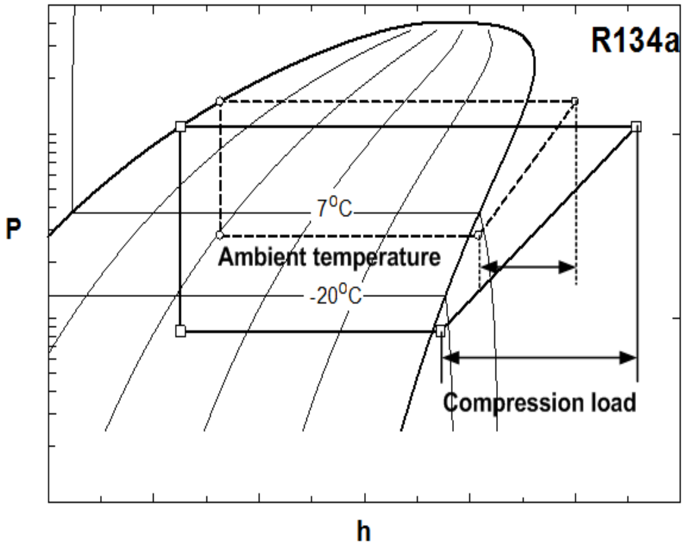



High-efficiency ecosystems, higher heating efficiency than electric heaters

# Introduction

## Background

- **Low ambient temperature**



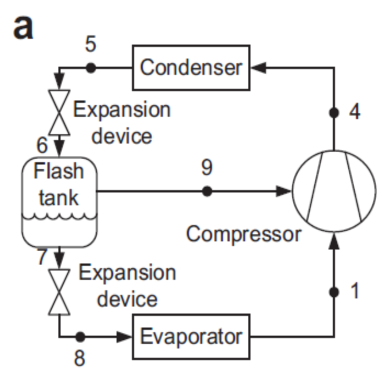

Severe decrease of heating capacity

- the increase in irreversibility during the compression process

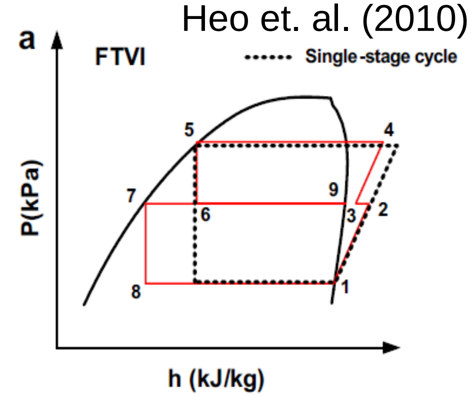
- the reduction in mass flow rate

- **Gas injection technique**

Heo et. al. (2010)




Flash tank vapor injection (FTVI)




Flash tank vapor injection (FTVI)

Increase in heating capacity & efficiency

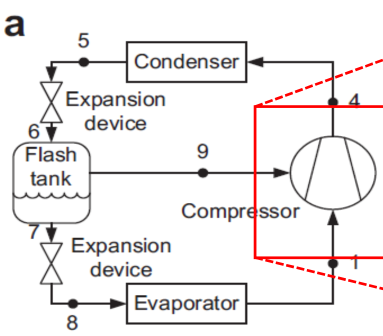
- the amount of heat absorbed in the evaporator increased

- the amount of refrigerant flowing through the condenser increased

- the rise in the average suction pressure

# Introduction

- **Injection scroll compressor**



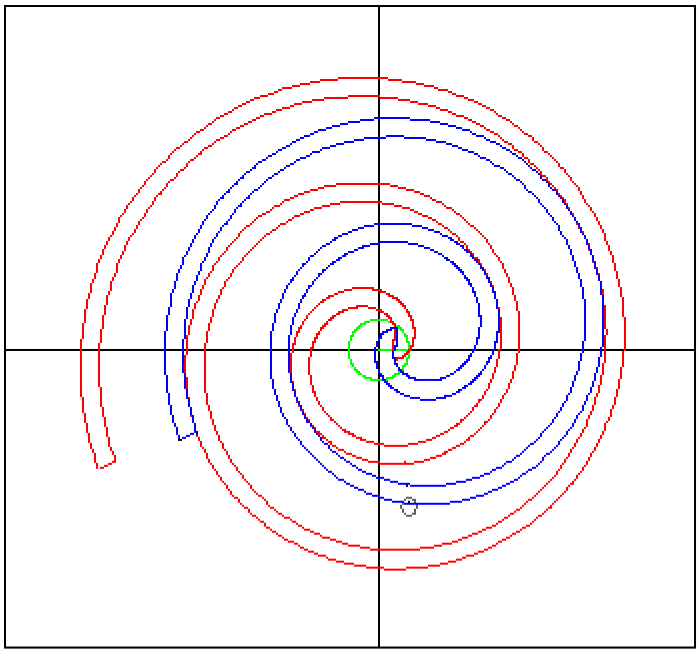

Flash tank vapor injection (FTVI) Heo et. al. (2010)

**Objectives**

- Adopt gas-injection technique to compressor of electric vehicle heat pump system
- Develop a simulation model
- Prove the validity of the simulation model
- Investigate characteristics of injection process with the orbiting angle

# Simulation modeling

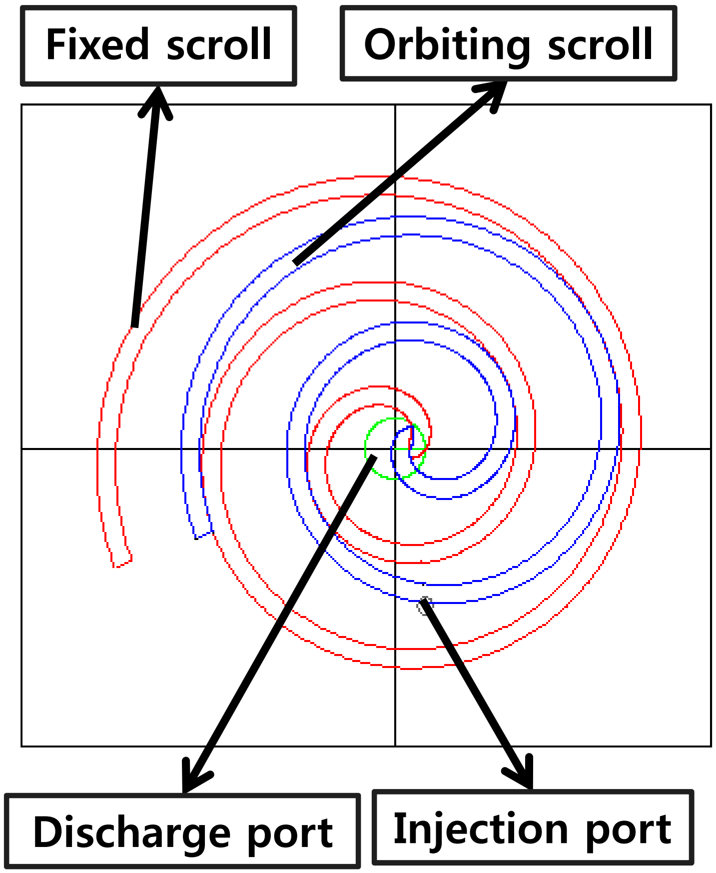
- **Specifications of scroll compressor**



| Design parameter | value |
| --- | --- |
| Working fluid | R134a |
| Displacement volume | 27 cc |
| Involute end angle | 1010 deg |
| Angle of injection hole | 1010-285 deg |

# Simulation modeling

- **Dynamic model**




## Input data

Scroll compressor geometry

Compressor inlet condition (P ,T , h)

Compressor outlet condition (P)

Injection port condition (P, T, h)

## Output data

Compressor outlet condition (T , h)

Compressor power

Mass flow rate (Condenser, Evaporator, Injection)

Injection Ratio

# Simulation modeling

- **Governing equation**

**Mass Conservation**

$$\frac{dm}{d\theta}=\frac{dm_i}{d\theta}-\frac{dm_o}{d\theta}+\frac{dm_{inj}}{d\theta}$$

**Energy Conservation**

$$\frac{dQ}{d\theta}+\Sigma\frac{dm_i}{d\theta}h_i+\Sigma\frac{dm_{inj}}{d\theta}h_{inj}=\frac{dW_i}{d\theta}+\Sigma\frac{dm_o}{d\theta}h_o+\frac{d}{d\theta}(mu)$$

$$\frac{dT}{d\theta}=\frac{\frac{1}{m}\left[\frac{dm_i}{d\theta}(h_i-h)+\frac{dm_{inj}}{d\theta}(h_{inj}-h)-\frac{dm_o}{d\theta}(h_o-h)\right]-\left[(\frac{\partial h}{\partial v})_T-(\frac{\partial P}{\partial v})_T v_c\right]\frac{dv}{d\theta}}{\left[(\frac{\partial h}{\partial T})_v-(\frac{\partial P}{\partial T})_v v_c\right]}$$

**Pressure & Enthalpy calculation**

$$\frac{dP}{d\theta}=(\frac{\partial P}{\partial T})_v\frac{dT}{d\theta}+(\frac{\partial P}{\partial v})_T\frac{dv}{d\theta}$$

$$\frac{dh}{d\theta}=(\frac{\partial h}{\partial T})_v\frac{dT}{d\theta}+(\frac{\partial h}{\partial v})_T\frac{dv}{d\theta}$$

# Simulation modeling

- **Leakage & Injection mass flow rate modeling**

**one-dimensional compressible flow equation in a nozzle with an assumption of an isentropic process**

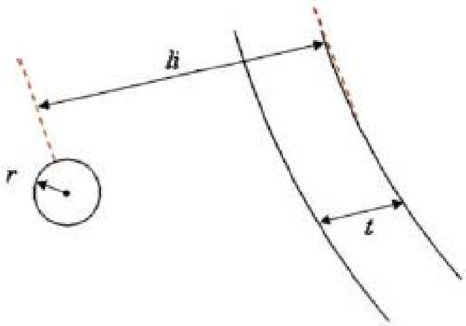
$$\frac{dm}{dt} = C_{\mathrm{d}} A P_{\mathrm{up}} \sqrt{\frac{2k}{R(k-1)T_{\mathrm{up}}}\left[\left(\frac{P_{\mathrm{down}}}{P_{\mathrm{up}}}\right)^{2/k} - \left(\frac{P_{\mathrm{down}}}{P_{\mathrm{up}}}\right)^{(k+1)/k}\right]} \quad \text{for} \left(\frac{P_{\mathrm{down}}}{P_{\mathrm{up}}}\right) \geq \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$$

$$\frac{dm}{dt} = C_{\mathrm{d}} A P_{\mathrm{up}} \sqrt{\frac{2k}{RT_{\mathrm{up}}}\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}} \quad \text{for} \left(\frac{P_{\mathrm{down}}}{P_{\mathrm{up}}}\right) < \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$$

# Simulation modeling

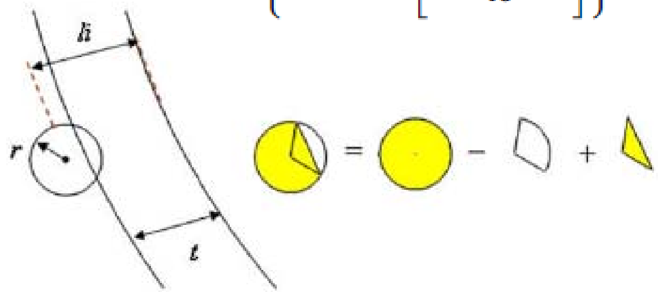
- **Injection hole area** Liu et al. (2009)

$$A_{By} = \pi r^2$$



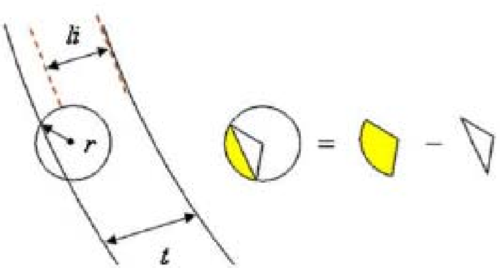

Condition (A)

$$A_{By} = \left\{ \pi - \tan^{-1}\left[\frac{(r^2 - lo^2)^{0.5}}{lo}\right] \right\} r^2 + lo(r^2 - lo^2)^{0.5}$$



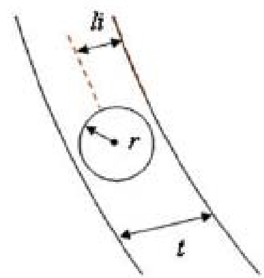

Condition (B)

$$A_{By} = r^2 \tan^{-1}\left[\frac{(r^2 - lo^2)^{0.5}}{lo}\right] - lo(r^2 - lo^2)^{0.5}$$




Condition (C)

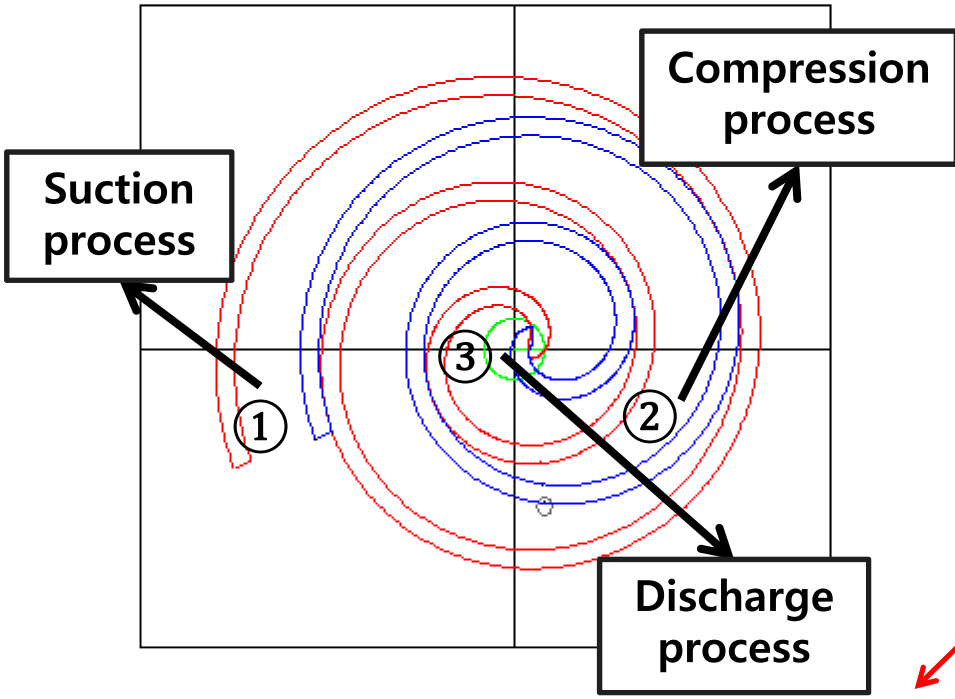
$$A_{By} = 0.$$



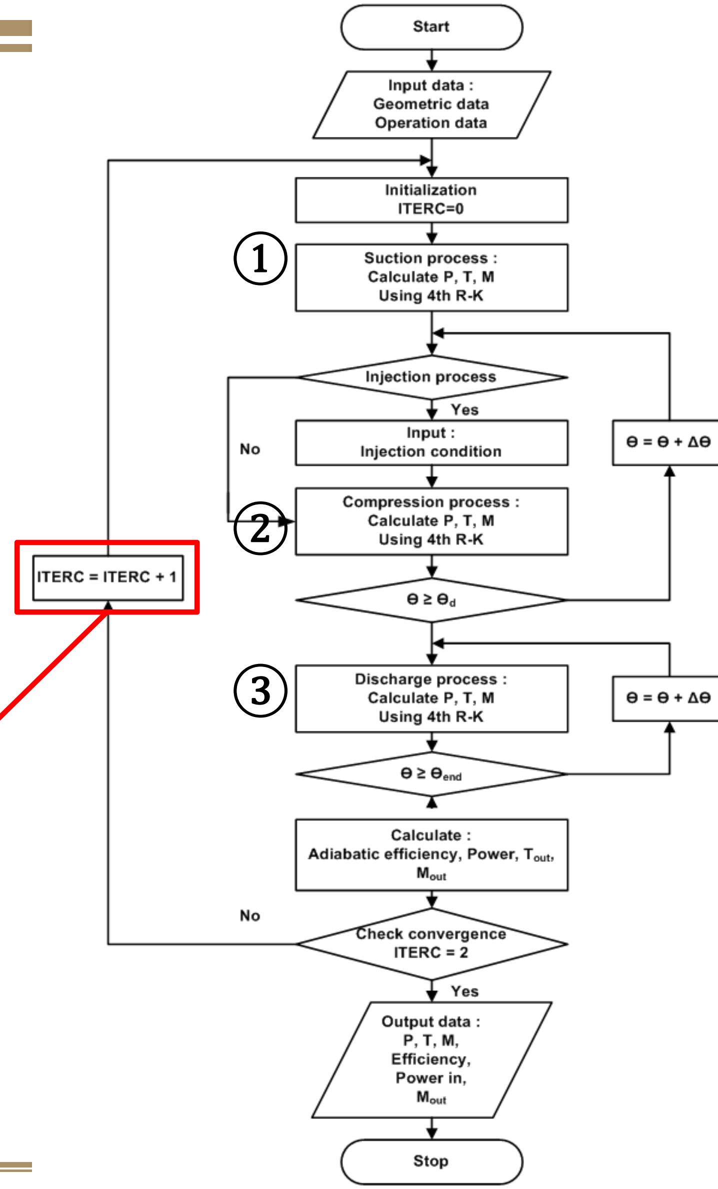

Condition (D)

# Simulation modeling

- Individual compressor process

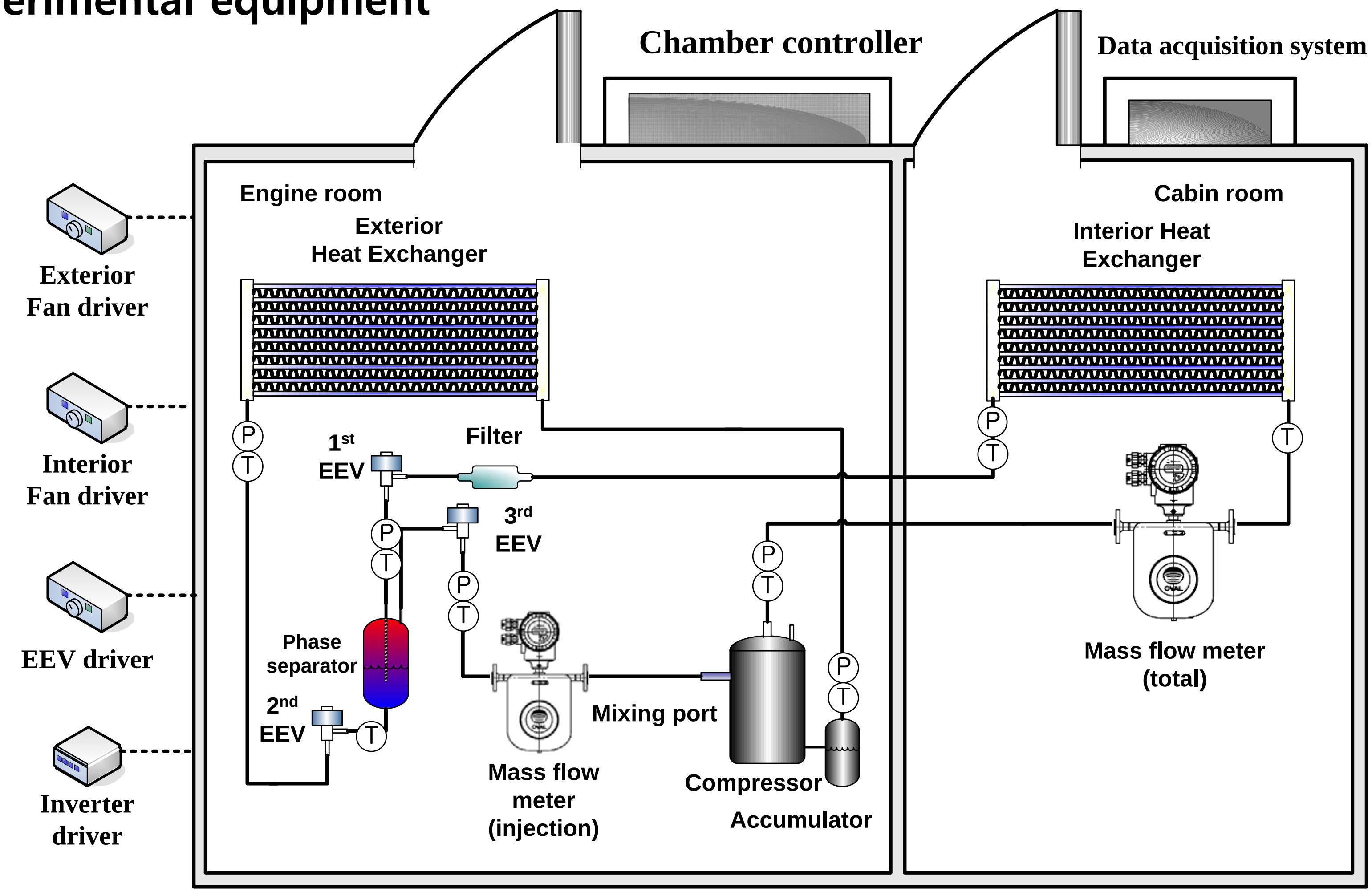



| ITERC | 0 | 1 | 2 |
|---|---|---|---|
| Leakage model | x | x | o |
| Suction gas heating | x | o | o |



# Model validation

- **Experimental equipment**



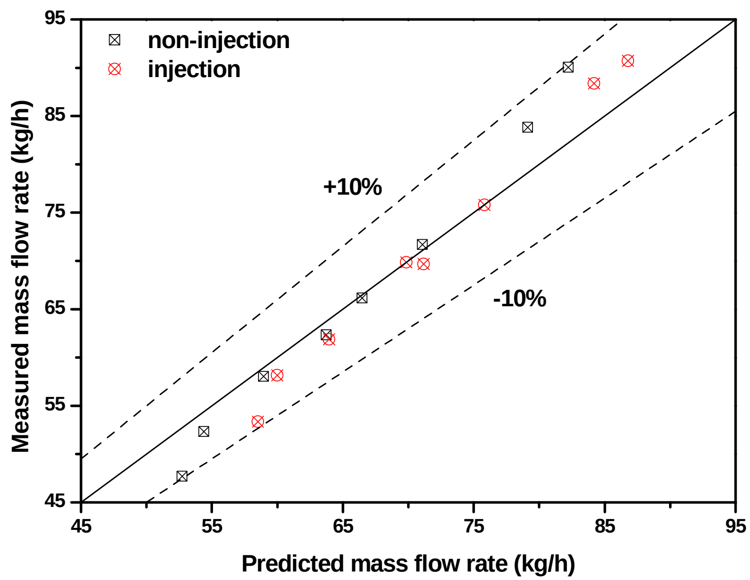
# Model validation

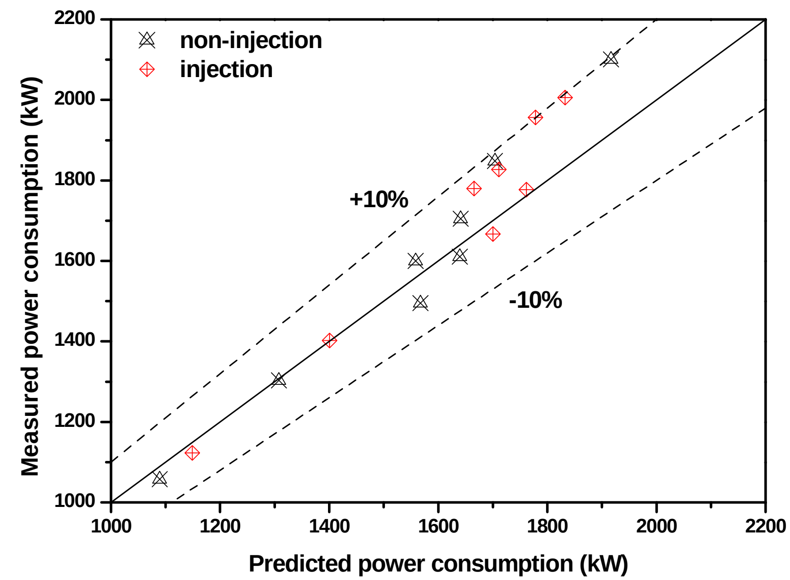
- **Validation condition**

| Parameter | Unit | Value |
|---|---|---|
| **Outdoor temperature** | ℃ | 7 ~ -15 |
| **Outdoor humidity** | % | 87 |
| **Indoor temperature** | ℃ | 20 |
| **Indoor humidity** | % | 59 |
| **Compressor frequency** | rpm | 3600 ~ 7200 |

**Korean Standards Association, KS air-conditioner: KS C 9306**

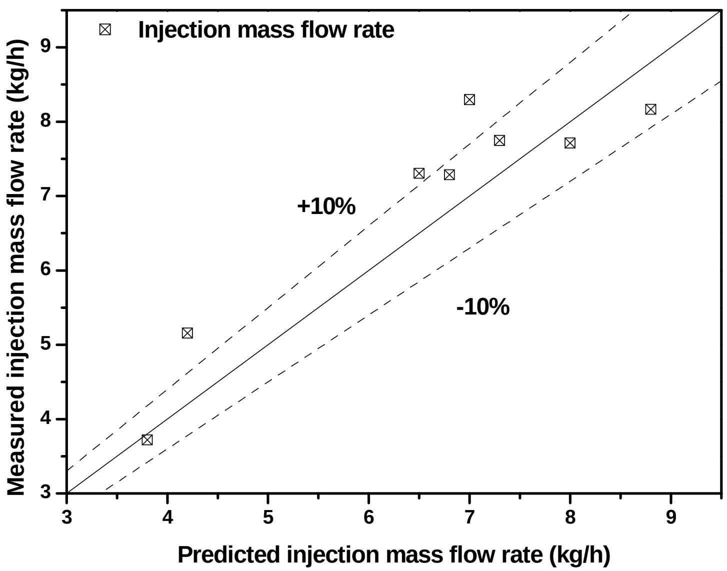
# Model validation

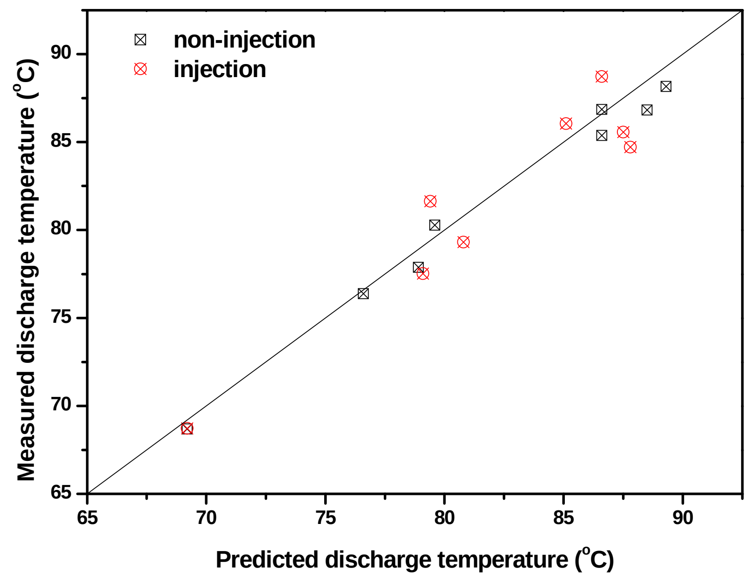



- The maximum difference between the predicted and measured data
  - Mass flow rate : 9.53%, Power consumption : 10.02%
  - The deviations within 10% for approximately 95% of the measured data

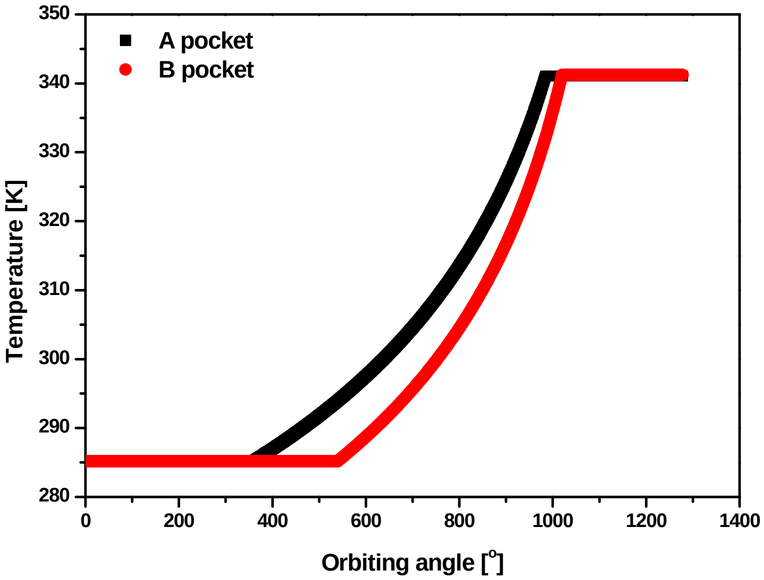
# Model validation

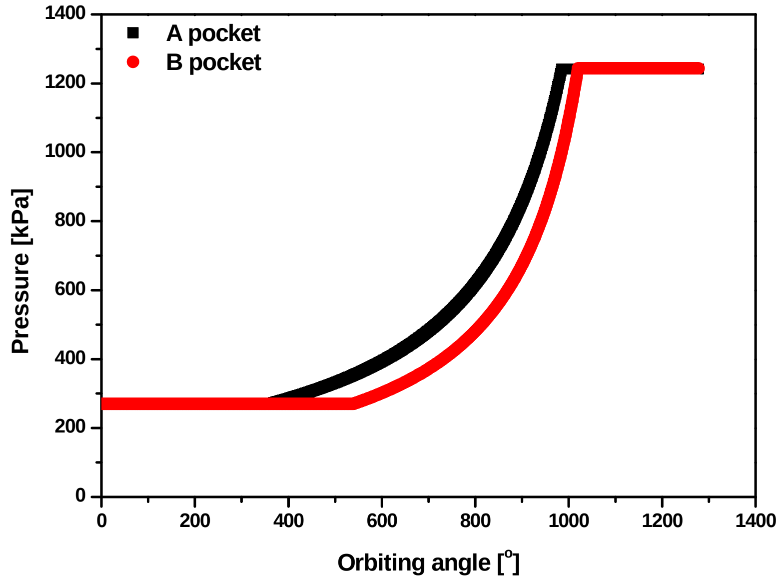



- The maximum difference between the predicted and measured data
  - Injection mass flow rate : 22.79%, Discharge temperature : 3.09 K
  - The deviation of injection mass flow rate within 10% for approximately 67.5% of the measured data

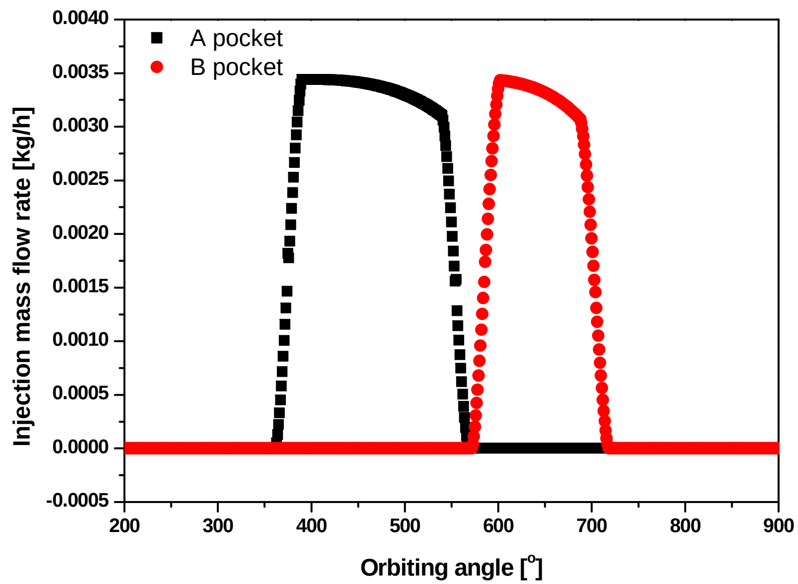
# Results and discussion




- The detailed process of simulation model
  - Using 4th Runge-Kutta method
  - Suction processes of A and B pockets were within angle of 0-360° and 180-540°, respectively
  - Tendency of the temperature and pressure was different

# Results and discussion




- Characteristic of injection process
  - Injection hole angle : 1010-285°
  - Because of asymmetric geometry, each of the pockets had different injection period
  - A slight loss was observed due to the late injection

# Conclusions

- A simulation model of the injection scroll compressor in a heat pump for electric vehicles was developed.
- The compressor model was based on the thermodynamic governing equations and fourth-order Runge-Kutta method.
- In the model validation, the simulation results were consistent with the experimental data.
- The injection characteristics with the orbiting angle were investigated.

Thank you.

Any question?