Positive Displacement Compressors with Liquid and Vapor Injection

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Be The Difference.

OUTLINE

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- **Introduction**
  - Motivation for liquid and vapor injection
  - Methods for implementing injection
- **Modeling the vapor compression cycle with injection**
- **Developing a comprehensive compressor model with injection**
  - Single-phase refrigerant injection
  - Two-phase refrigerant injection
- **Example: Modeling vapor injection in the spool compressor**
- **Summary**

BACKGROUND

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Liquid and vapor injection both provide a cooling effect during the compression process

- Injected refrigerant is at a lower temperature than refrigerant in the working chamber

Goals of refrigerant injection depend upon the application:

- Reduce compressor discharge temperature Holtzapple
- Increase cycle capacity
- Increase cycle coefficient of performance (COP)

Method of implementation depends upon goals:

- Economization with flash tank or intermediate heat exchanger (IHX)
- Direct expansion from condenser exit

MOTIVATION

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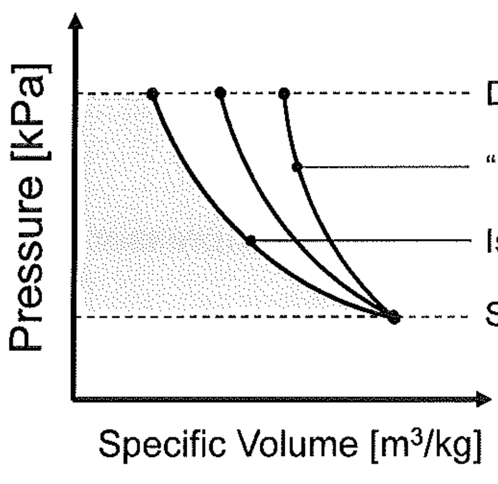
Cooling the refrigerant during the compression process

- Reduces the refrigerant temperature and enthalpy
- Increases the refrigerant density (reduces specific volume)



$$w_{rev} = -\int v dP$$

IMPLEMENTATION

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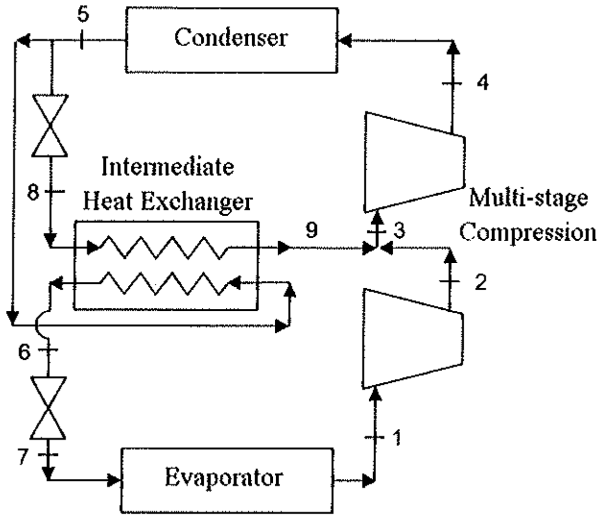
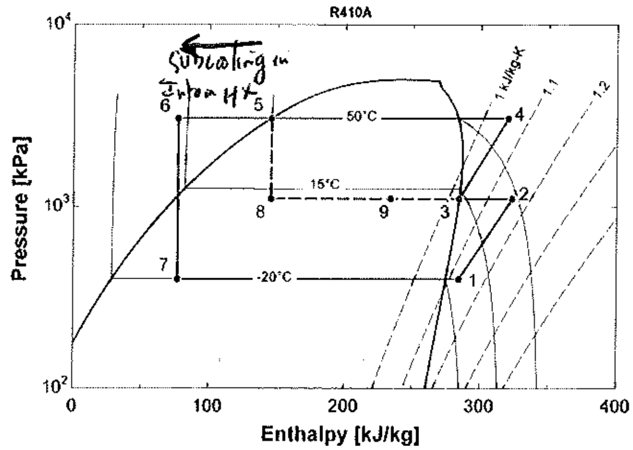
Vapor Injection

Economized cycle with intermediate heat exchanger (IHX) and multi-stage compressor





Trade off — subcooling increases capacity but part of ṁ is diverted reducing capacity
is cup half full or half empty

IMPLEMENTATION

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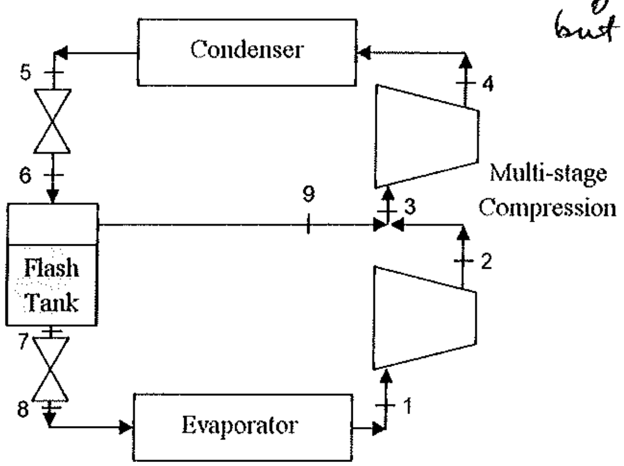
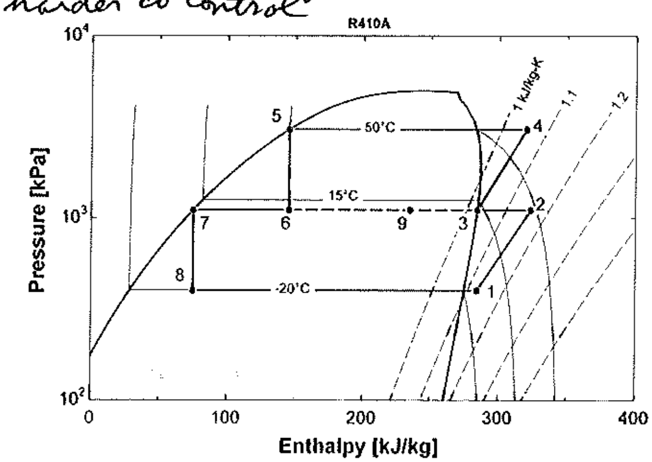
Vapor injection

Economized cycle with flash tank or phase separator and multi-stage compressor

Equivalent to IHX cycle of $\varepsilon_{IHX} = 1.0$
so generally better performance
but harder to control





IMPLEMENTATION

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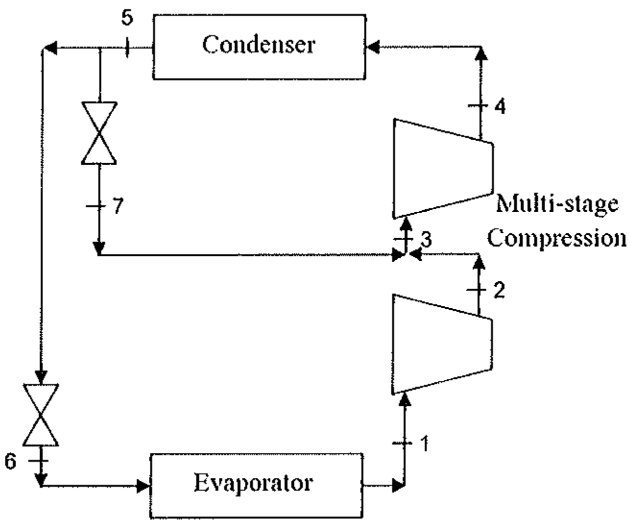
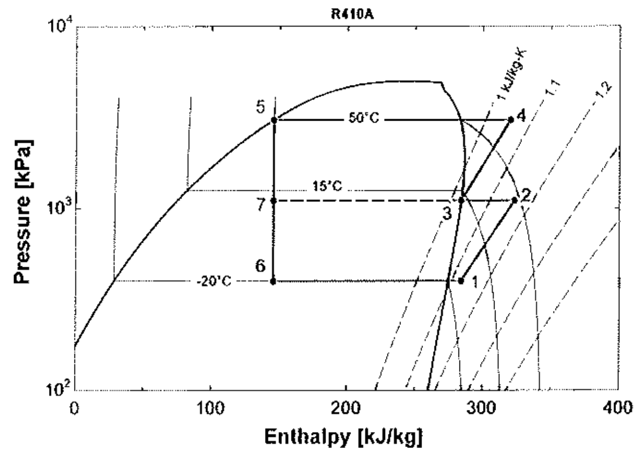
Reduces W but

Cycle with direct expansion from condenser exit and multi-stage compressor

Does not increase capacity except to extent of





IMPLEMENTATION

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Economized cycle:

- **Both configurations theoretically and experimentally shown to improve capacity and COP**
- **IHX provides performance identical to a flash tank when the heat exchanger is 100% effective, but performance degrades with decreasing effectiveness**
- **IHX can be used to inject superheated vapor, whereas flash tank is limited to saturated vapor**

Cycle with direct expansion from condenser exit:

- **Shown to significantly reduce discharge temperature**
- **Smaller impact on capacity and COP**

IMPLEMENTATION

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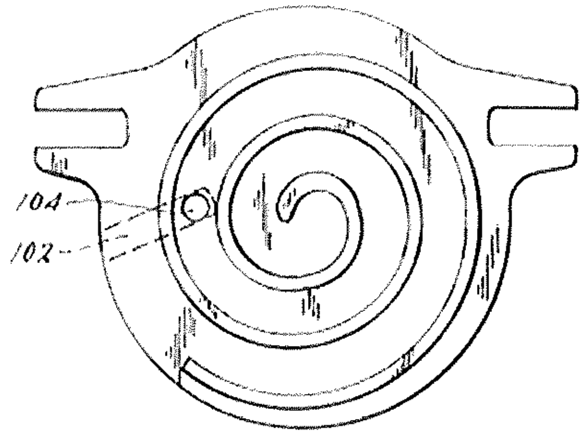
Compressors with ports for refrigerant injection enable economization within a single-stage compressor

- Injection has been demonstrated with scrolls
- Number of injection ports can be increased relatively easily and at low cost



102: Vapor Injection Port
104: Vapor Injection Passage
(Perevozchikov, 2003)

OUTLINE

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CYCLE MODEL WITH INJECTION

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Develop a cycle model to predict the theoretical limit to performance improvements with economized refrigerant injection

Assume:

- Constant compressor efficiency
- Instantaneous injection and mixing process (isobaric)
- Adiabatic mixing process

Specify:

- Compressor efficiency
- Condensing and evaporating temperatures
- Degree of subcooling and superheat

CYCLE MODEL WITH INJECTION

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Specify three of the following injection conditions:

- Injection pressure
- Quality of injected refrigerant (if two-phase), or temperature of injected refrigerant (if single-phase)
- Enthalpy of injected refrigerant
- Quality of refrigerant entering the second expansion valve (following separation from the injection stream in a flash tank)
- Mass fraction of refrigerant through injection line
- Quality (two-phase) or temperature (single-phase) in working chamber at end of mixing process
- Temperature at end of compression process

Remaining properties can be determined from mass and energy balances on separation and mixing processes

CYCLE MODEL WITH INJECTION

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Example:

- **User specifies injection pressure**
- **User specifies that the refrigerant in the working chamber is saturated vapor after mixing with the injected refrigerant**
- **User specifies that the refrigerant entering the second expansion valve is saturated liquid**
- **Model calculates:**
  - Mass flow ratio through the injection port
  - Enthalpy and quality of the refrigerant entering the evaporator, and thus the capacity

CYCLE MODEL WITH INJECTION

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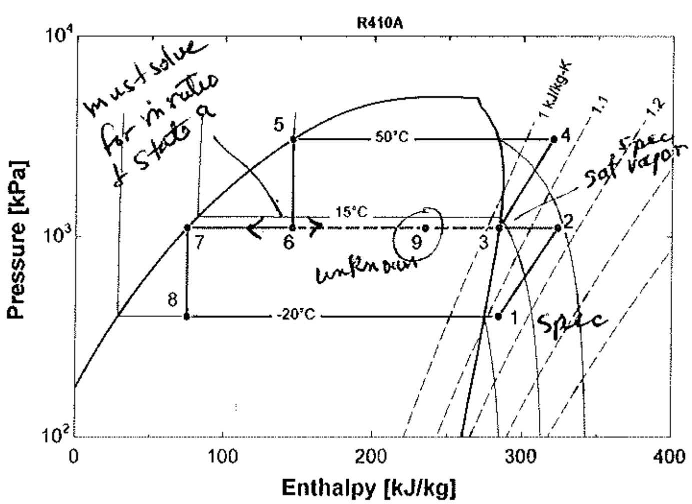

Define mass flow ratios:

$$r_{inj} = \frac{\dot{m}_{inj}}{\dot{m}_{cond}}$$

$$r_{comp} = \frac{\dot{m}_{comp}}{\dot{m}_{cond}}$$

Isentropic efficiency: specified

$$\eta_s = \frac{h_{2s} - h_1}{h_2 - h_1}$$

Valve energy balance:

$$h_6 = h_5$$

$$h_8 = h_7$$

CYCLE MODEL WITH INJECTION

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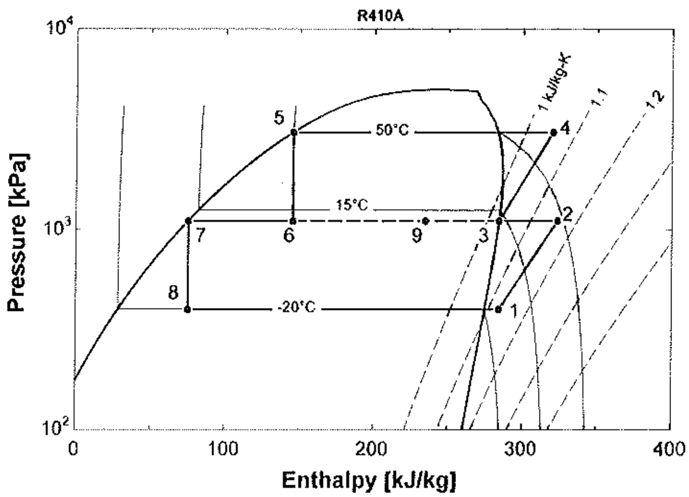

Conservation of Mass:

$$r_{inj} = r_{cond} - r_{comp}$$

Conservation of Energy:

$$r_{comp} = r_{cond}\left(\frac{h_6 - h_3}{h_7 - h_2}\right)$$

$$h_9 = \frac{r_{cond} \cdot h_6 - r_{comp} \cdot h_7}{r_{inj}}$$

CYCLE MODEL WITH INJECTION

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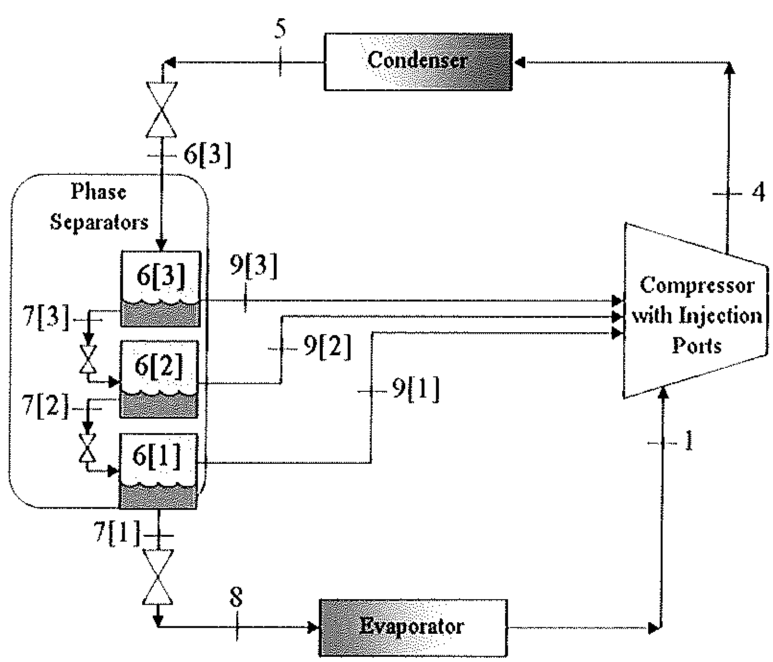
Increasing the number of compressor stages used with economization increases cycle COP (Jung et al., 1999)

- Similar trend is expected with increasing number of injection ports (Mathison et al., 2011)



CYCLE MODEL WITH INJECTION

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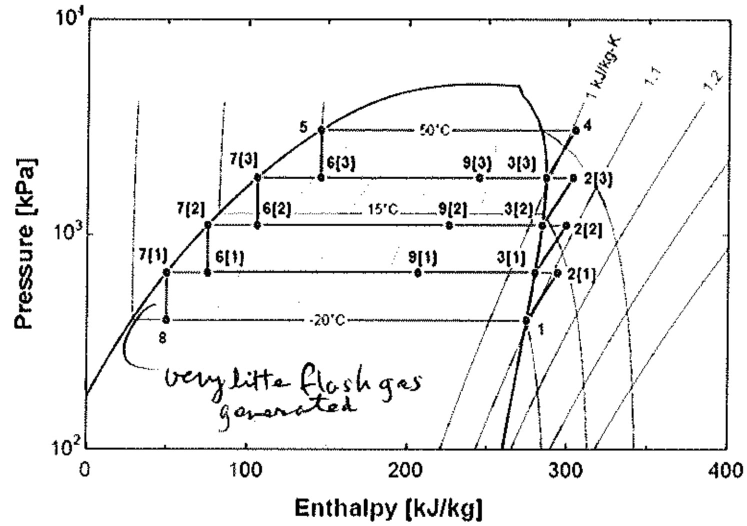
Economized R-410A vapor compression cycle with three injection ports

- Evaporating at -20°C
- Condensing at 50°C
- Compressor efficiency of 70%
- Injection results in saturated vapor state in compressor
- Model predicts 33% improvement in cooling COP with three ports



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COMPRESSOR MODEL WITH INJECTION

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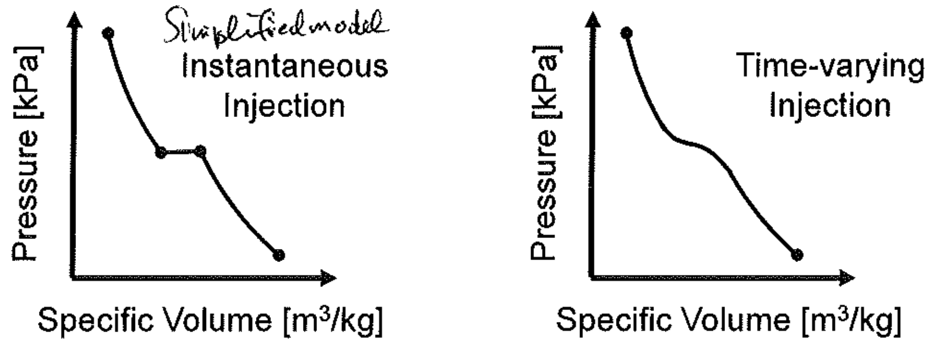
Comprehensive compressor models aim to provide a more accurate prediction of performance with injection

- Analyze the injection process in smaller time steps
  - Variations in chamber properties during the process
  - Leakage to adjacent chambers during the process
  - Heat transfer to chamber walls during the process
- Predict impact of injection on compressor efficiency



COMPRESSOR MODEL WITH INJECTION

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One approach is to model the injection port in the same manner as the suction port, assuming constant properties in the injection line and specifying:

- **Injection pressure**
- **Injection temperature (single-phase) or quality (two-phase)**

Characteristics of the compressor determine the mass flow rate of refrigerant through the injection port

- **Size and location of the port**
- **Method for controlling timing of injection process**
  - Continuously open like Recip or rolling piston compr
  - Controlled by a valve or mechanism like scroll or "supercharged recip"
- **Conditions in the working chamber**

COMPRESSOR MODEL WITH INJECTION

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Injection ports can be analyzed in the same manner as other flow paths, assuming: (as usual)

- **Isentropic flow of a compressible (real) ideal gas through the port**

$$\dot{m} = c_v A P_h \sqrt{\frac{2k}{(k-1)RT_h}\left[P_r^{(2/k)} - P_r^{(k+1/k)}\right]} \quad \text{where} \quad P_r = \frac{P_l}{P_h}$$

c_v = Constant volume specific heat
k = Specific heat ratio
A = Cross-sectional area of path
R = Gas constant
P_r = Pressure ratio
P_h = High-side pressure
P_l = Low-side pressure
T_h = High-side temperature

COMPRESSOR MODEL WITH INJECTION

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Injection ports can be analyzed in the same manner as other flow paths, assuming:

- **Instantaneous mixing of the flow with refrigerant in the compressor working chamber, which is accounted for in the mass and energy balances:**

$$\frac{d\rho}{d\theta} = \frac{1}{V}\left[-\rho\frac{dV}{d\theta} + \frac{1}{\omega}\left(\sum \dot{m}_{in} - \sum \dot{m}_{out}\right)\right]$$

$$\frac{dT}{d\theta} = \frac{-\rho h\frac{dV}{d\theta} - \left(uV + \rho V\frac{\partial u}{\partial \rho}\right)\frac{\partial \rho}{\partial \theta} + \frac{1}{\omega}\left(\dot{Q} + \sum \dot{m}_{in}h_{in} - \sum \dot{m}_{out}h_{out}\right)}{\rho V\frac{\partial u}{\partial T}}$$

COMPRESSOR MODEL WITH INJECTION

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The overall mass and energy balances used to determine convergence of compressor model must be updated to include injection flow:

$$\dot{m}_s + \dot{m}_{inj} = \dot{m}_d$$

$$\dot{W}_{in} = \dot{m}_d h_d - \dot{m}_s h_s - \dot{m}_{inj} h_{inj} - \dot{Q}_{in}$$

IN ADDITION, the mass and energy balance on the separation process (flash tank or IHX) must converge:

mass $$\dot{m}_s + \dot{m}_{inj} = \dot{m}_d$$

energy $$0 = \dot{m}_d h_5 - \dot{m}_{inj} h_{inj} - \dot{m}_s h_7$$

In this case, must iteratively determine h_7

COMPRESSOR MODEL WITH INJECTION

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Summary for analyzing the injection port in the same manner as the suction port:

- **User specifies that a mechanism controls flow through the port and it is open to the compression pocket over a specified range of angles**
- **User specifies injection pressure**
- **User specifies that the injected refrigerant is saturated vapor**
- **Model calculates:**
  - Mass flow rate through the injection port
  - Enthalpy and quality of the refrigerant entering the second expansion valve (quality must fall within a range of feasibility)
  - Enthalpy and quality of the refrigerant entering the evaporator, and thus the capacity

flash tank quality constraint

COMPRESSOR MODEL WITH INJECTION

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Alternative approaches to characterizing the injection process

Specify how the timing of the injection process is controlled:

- Continuously open
- Controlled by a valve or mechanism

Specify TWO of the following injection conditions:

- Injection pressure
- Quality of injected refrigerant (if two-phase), or temperature of injected refrigerant (if single-phase)
- Enthalpy of injected refrigerant
- Quality of refrigerant entering the second expansion valve (following separation from the injection stream in a flash tank)
- Mass fraction of refrigerant through injection line not recommended
- Quality (two-phase) or temperature (single-phase) in working chamber at end of mixing process
- Temperature at end of compression process not recommended

COMPRESSOR MODEL WITH INJECTION

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Alternative analysis example:

- **User specifies that a mechanism controls flow through the port and it is open to the compression pocket over a specified range of pressures** very hypothetical
- **User specifies that the injected refrigerant is saturated vapor**
- **User specifies that the refrigerant entering the second expansion valve is saturated liquid**
- **Model calculates:**
  - Mass flow rate through the injection port based on an initial guess for injection pressure
  - Updated value for injection pressure such that the rate of vapor generation in the flash tank converges with the rate of vapor injection to the compressor

COMPRESSOR MODEL WITH INJECTION

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Additional steps for improving model accuracy:

currently assume const P in injection line $P(\theta) = const$

- **Account for time-varying conditions in the injection line through alternate assumptions:**
  - Constant pressure and quality in the flash tank
  - Constant pressure and temperature exiting the condenser
- **Account for impact of changing evaporator inlet conditions on suction state**
- **Account for impact of changing mass flow rate through the condenser on degree of subcooling**

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MODELING TWO-PHASE INJECTION

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Dutta et al. (1996) analyzes three methods for modeling two-phase injection in a reciprocating compressor:

- Droplet model that relates heat transfer to droplet size
- Slugging model that determines heat transfer necessary to maintain a saturated vapor
- Homogeneous model that determines heat transfer necessary to equalize the liquid and vapor temperatures

Concludes that homogeneous model provides sufficient accuracy:

$$mh = m_l h_l + m_g h_g$$

MODELING TWO-PHASE INJECTION

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The homogeneous model essentially assumes that any liquid droplets evaporate instantaneously

Models developed following this approach provided satisfactory agreement with experimental results:

- Dutta et al. (2001)
- Yamazaki et al. (2002)
- Wang et al. (2007, 2008, 2009a, 2009b)

MODELING TWO-PHASE INJECTION

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Wang et al. (2008) recommends the following equation for mass flow rate in order to account for the presence of liquid in the injection line:

$$\dot{m} = \frac{C_d A}{x/\rho_{g,d} + (1-x)/\rho_l} \sqrt{2\left[x\left(\frac{k}{k-1}\right)\left(\frac{P_u}{\rho_{g,u}} - \frac{P_d}{\rho_{g,d}}\right) + (1-x)\left(\frac{P_u - P_d}{\rho_l}\right)\right]}$$

C_d = Real gas correction factor
k = Specific heat ratio
P_d = Downstream pressure
P_u = Upstream pressure
x = Quality

$\rho_{g,d}$ = Downstream gas density
$\rho_{g,u}$ = Upstream gas density
ρ_l = Liquid density
ρ_u = Upstream density

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SPOOL MODEL WITH INJECTION

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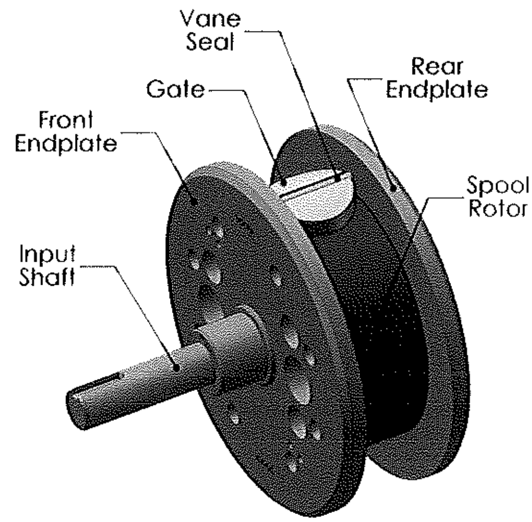
Need detailed spool compressor model to

- Improve prototype design without injection
- Evaluate effect of multiple injection ports

(Toroid Engine (similar to rotary vane cmpr)

Spool design aims to reduce leakage and friction losses

- Gate motion controlled by cam
- Face plates rotate with the crankshaft



(Kemp et al., 2010)

SPOOL MODEL WITH INJECTION

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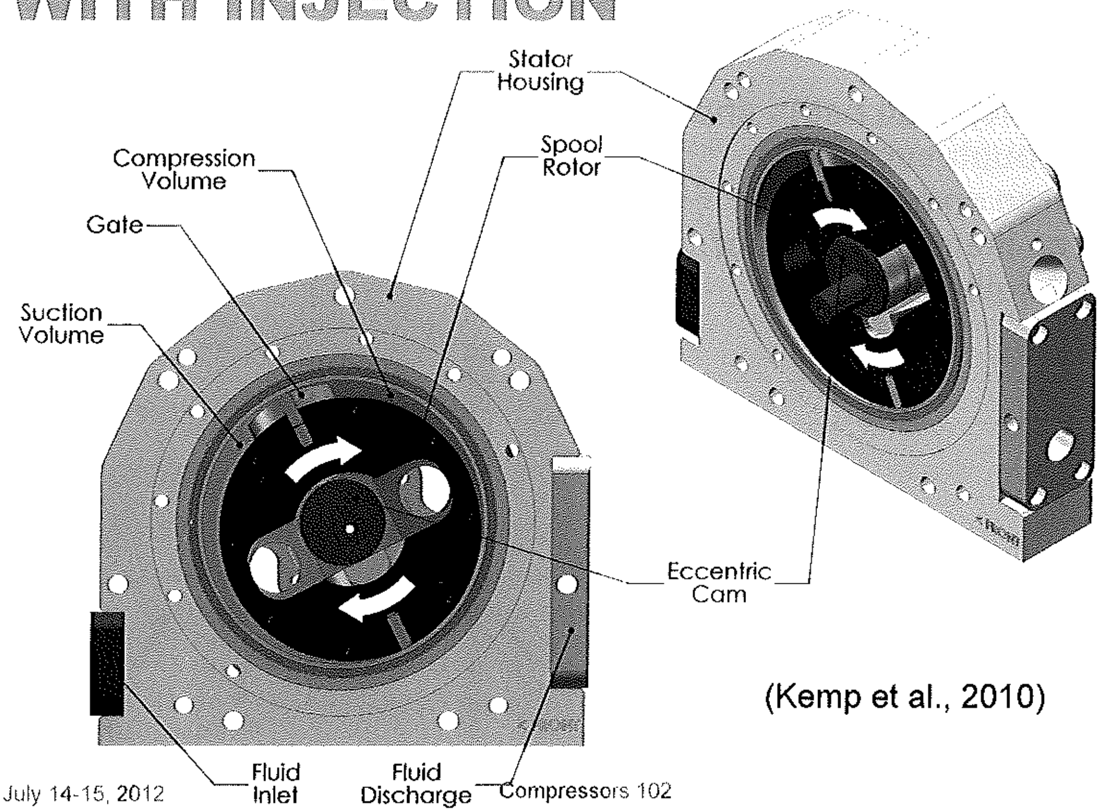

(Kemp et al., 2010)

SPOOL MODEL WITH INJECTION

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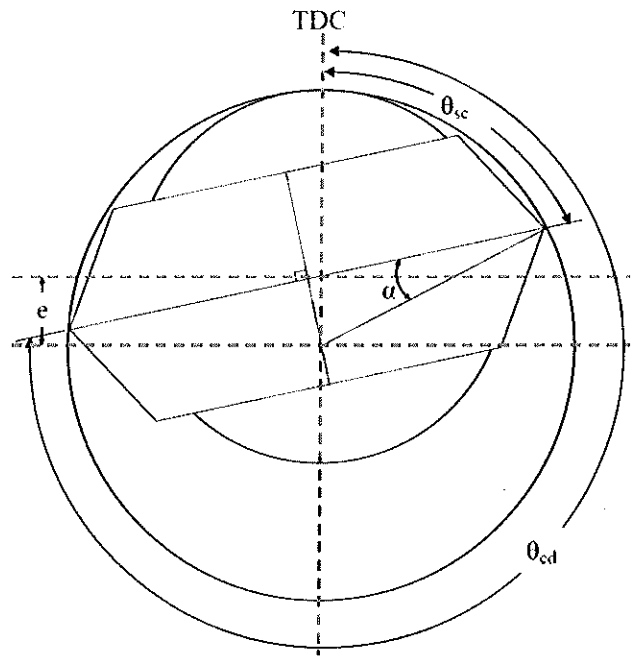
Define three control volumes in the compressor:

- **Suction chamber**
- **Compression chamber**
- **Discharge chamber**



SPOOL MODEL WITH INJECTION

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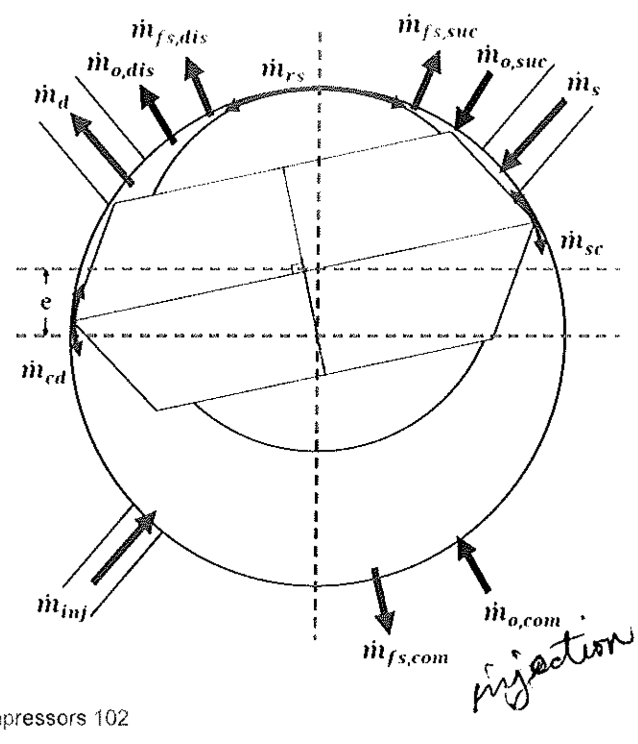
Modeled leakage paths and flow through suction, discharge and injection ports as isentropic flow of compressible ideal gas



SPOOL MODEL WITH INJECTION

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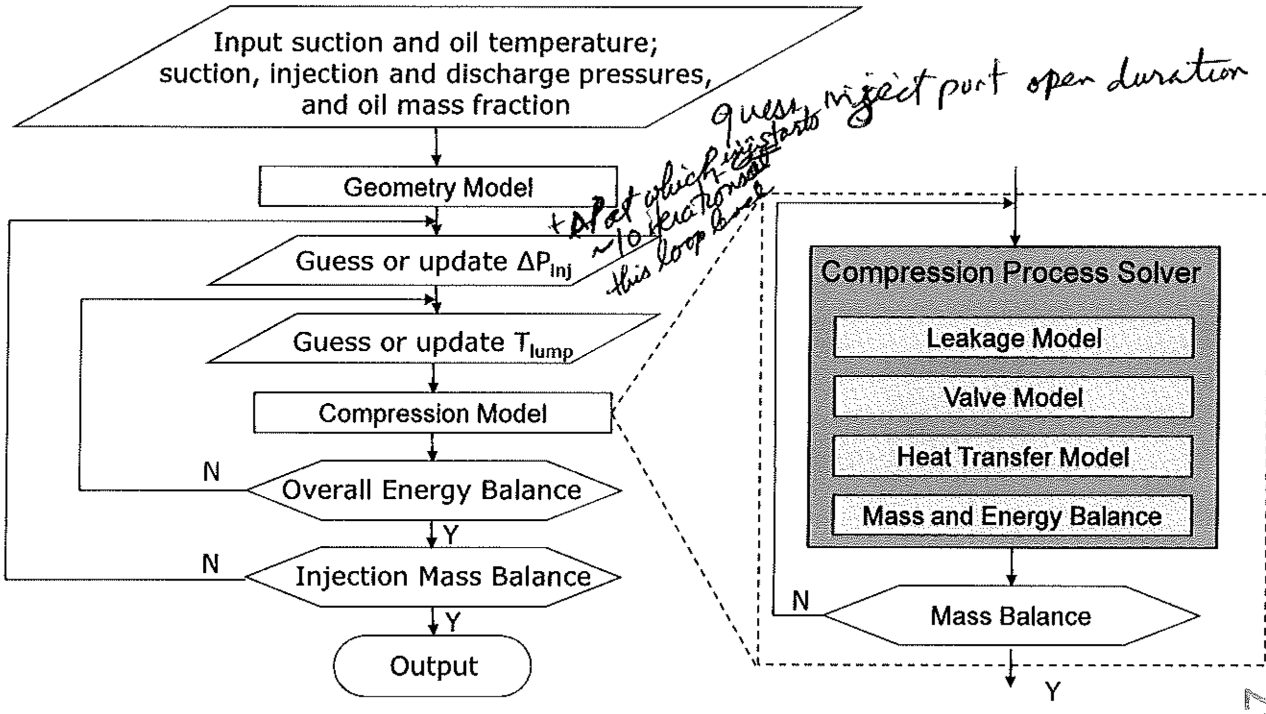

check feasibility & revise guess at many points

SPOOL MODEL WITH INJECTION

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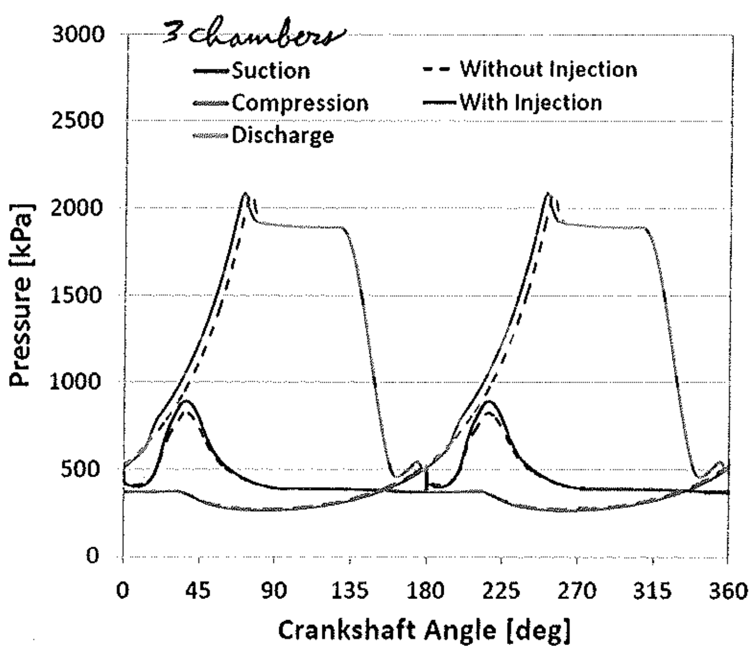

Effect of single injection port at 800 kPa on pressure profiles when T_s = 7.6°C, P_s = 391 kPa, P_d = 1889 kPa.

SPOOL MODEL WITH INJECTION

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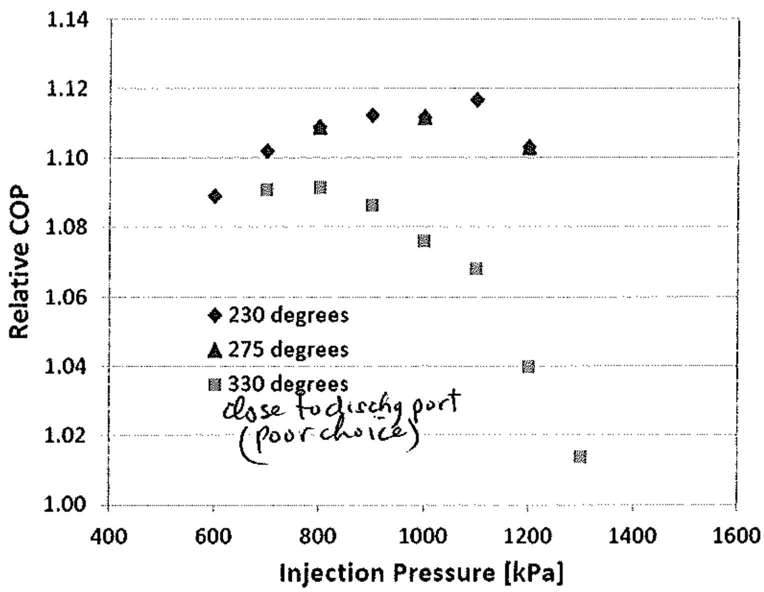

Effect of single 1.27-cm diameter port on R-22 cycle performance when T_s = 7.6°C, P_s = 391 kPa, P_d = 1889 kPa.

SPOOL MODEL WITH INJECTION

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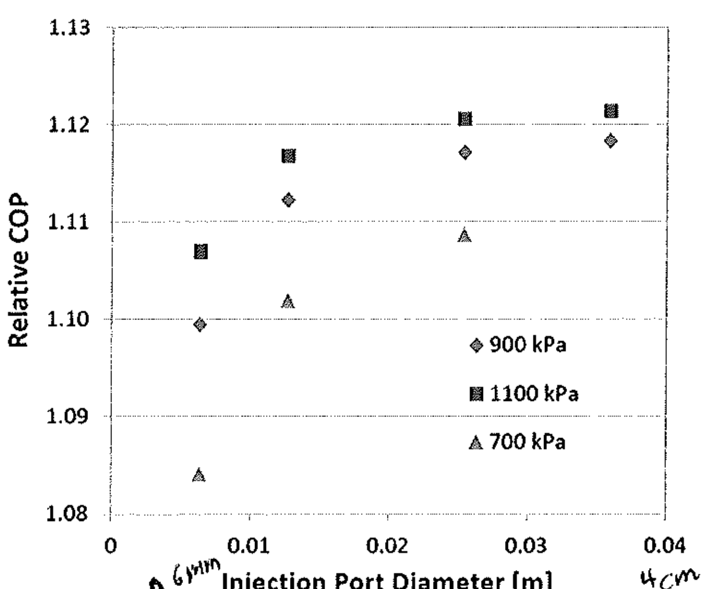

Effect of single port located at 230° on R-22 cycle performance when T_s = 7.6°C, P_s = 391 kPa, P_d = 1889 kPa.

larger port → shorter mixing duration (instant mixing is ideal)

SPOOL MODEL WITH INJECTION

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Model Results for Spool Compressor with and without Vapor Injection when $T_s = 7.6°C$, $P_s = 391$ kPa, $P_d = 1889$ kPa.

	Two Ports	One Port	No Ports
Low Injection Pressure, kPa	700	1100	-
High Injection Pressure, kPa	1200	-	-
Discharge Temperature, °C	70.28	71.71	74.41
Power Consumption, kW	2.51	2.45	2.38
Mass Flow Rate, kg/hr	53.2	49.5	42.9
Normalized Specific Power	0.85	0.89	1
COP	0.870	0.839	0.751
Normalized COP	1.16	1.12	1
Normalized Capacity	0.99	1.00	1
Isentropic Efficiency (all low)	21.3%	21.2%	21.6%
Volumetric Efficiency	48.6%	45.2%	39.3%

due to less re-expansion ?
how is η_v defined

41

SUMMARY

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Theoretical and experimental studies have demonstrated the benefits of liquid and vapor injection

- **Decrease compressor discharge temperatures**
- **Increase cycle capacity and COP**

Liquid and vapor injection can be implemented in multiple cycle configurations

- **Economized cycle with a flash tanks or IHX**
- **Direct expansion from the condenser exit**

Cycle modeling provides a means for estimating cycle performance with injection

- **Assumes constant compressor efficiency**
- **Assumes instantaneous and adiabatic injection process**
- **Requires estimate of injected mass flow rate**

SUMMARY

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A comprehensive compressor model provides more information about the impact of injection

- **Breaks the injection process into smaller time steps**
- **Provides an estimate of the injected mass flow rate**
- **Can be used to study the impact of port design parameters**
- **Can be used to predict the impact of injection on compressor efficiency**

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what about Carrier ~1997?

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what's difference?

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