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Computer Simulation of Effects From Injection of Different Liquids in Screw Compressors

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COMPUTER SIMULATION OF EFFECTS FROM INJECTION OF DIFFERENT LIQUIDS IN SCREW COMPRESSORS

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ABSTRACT

This paper gives a short presentation of a method for computer simulation of effects on the performance of screw compressor from injection of different liquids. The method takes into account liquid evaporation, subsonic or sonic two-phase leakage, heat transfer between liquid-gas-metal, flashing of dissolved gas and friction losses due to viscous liquid between moving parts.
The presented theory is a complement to the theory presented in [1].

Calculation results from screw compressors used as dragster superchargers, in process gas and refrigeration are presented and discussed.

NOMENCLATURE

c_p	specific heat of gas at constant pressure	c_{liq}	specific heat of liquid
D_M	male rotor diameter	η	dynamic viscosity of gas
η_{mix}	dynamic viscosity of gas-liquid mixture	h	enthalpy of gas
h_{liq}	enthalpy of liquid	m_d	mass flow of gas through outlet port
m_{oil}	mass flow of injected oil	m_{liq}	mass flow of liquid
$m_{liq,evap}$	mass flow of evaporated liquid	$m_{\Delta p_{dry}}$	leakage mass flow of gas caused by pressure difference, dry compressor
n	exponent for laminar or turbulent flow	r_{evap}	heat of evaporation
ρ	density of gas	ρ_{liq}	density of evaporated-saturated liquid
ρ_{mix}	density of gas liquid mixture	T	temperature of gas in control volume
T_{amb}	ambient temperature	V	control volume
x	gas liquid mixture ratio	ω_M	male rotor angular speed

INTRODUCTION

In many screw compressor applications, liquid injection into the control volume is used as a means for sealing, cooling and lubrication. The most common liquid is oil, but in some cases water or methanol is also used.

The injected liquid complicates the performance calculation and special attention must be taken to:

- Leakage, which has to be treated as a two-phase subsonic or sonic flow.
- Heat transfer between liquid, gas and metal parts, which takes place before, during and after the passage of the screw compressor. With water or methanol injection it is necessary to take the evaporation of the liquid into consideration.
- Mass fraction of gas, which is in the injected liquid. Of special interest is the flashing and re-solution of refrigerants. This is an important parameter for refrigeration compressors.

- Friction losses due to viscous liquid between moving parts of different velocities.
- Friction losses due to pressure difference over the leakage paths.
- Displacement of liquid volume, which in the case of high pressure screw compressors to a significant degree influences the performance.
- Influence of position and number of liquid injection holes.

THEORY

Leakage

The leakage through the leakage paths in a liquid injected screw compressor is a 2-phase-flow type leakage, and it is necessary to include the effect of density and viscosity of the gas-liquid mixture in the leakage model. In those cases - when the screw compressor operates both with and without liquid injection - it is important to have a model than is useful for both subsonic and sonic dry and mixed flow conditions, without having any discontinuity between the two flow types.
A way to express the leakage caused by the pressure difference is to modify the isentropic flow formulas for dry screw compressors.

The gas-liquid mixture mass flow is then = $\left(m_{\Delta p_{dry}}\right)\cdot\left(\frac{\rho_{mix}}{\rho}\right)^{\frac{1}{2-n}}\cdot\left(\frac{\eta}{\eta_{mix}}\right)^{\frac{n}{2-n}}$

, where value $n \approx 1$ for laminar flow and $\approx 0,3$ for turbulent flow. Note that for $n = 0,$ no influence from viscocity is obtained.

Heat transfer

Since the screw compressor is used for a variety of different gases it is necessary to include the gas properties in the heat transfer calculations.

The heat transfer between gas and and metal
$= const\cdot\eta^{0,2}\cdot\rho^{0,8}\cdot c_p\cdot \mathrm{Pr}^{-2/3}\cdot\omega_M{}^{0,8}\cdot D_M{}^{0,8}\cdot V^{2/3}\cdot\left(T-T_{amb}\right)$

, where $\mathrm{Pr} = \mathit{Prandtl\ number} = \frac{c_p\cdot\eta}{\lambda}$

Note that this heat transport is a loss of energy from the compressor control volume, which means that it influences the discharge temperature.

The heat transfer between gas and injected liquid
$= const\cdot\eta^{0,2}\cdot\rho^{0,8}\cdot c_p\cdot \mathrm{Pr}^{-2/3}\cdot\omega_M{}^{0,8}\cdot D_M{}^{0,8}\cdot(1-x)\cdot V\cdot\left(T-T_{liq}\right)$

This heat transport is not a loss of energy from the compressor control volume. The energy is only transferred from the gas to the liquid.

Discharge temperature
at liquid injection before or into the screw compressor

Energy balance gives the discharge temperature = $\frac{\left(h_{liq}+h-m_{liq,evap}\cdot r_{evap}\right)}{\left(m_d\cdot c_p+m_{liq}\cdot c_{liq}\right)}$

, where $m_{liq,evap} \leq m_{liq}$ at saturation and $m_{liq,evap} = m_{liq}$ at temperatures above saturation.

Flashing of dissolved refrigerant in the oil

The oil is injected at condition ① and the flashing takes place approx. along constant temperature to condition ②. See fig.1.

The amount of flashed gas is then

$\dot{m}_{oil} \cdot (x_1 - x_2) \cdot corr$, where *corr* corrects for delay in the flashing.

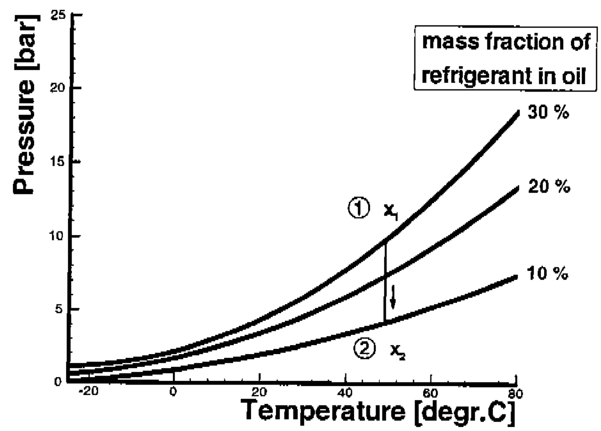

Fig. 1. Dissolution of refrigerant in oil.

Friction losses

These losses are calculated from a modified theory presented in [2] and covers:

- Friction losses due to velocity difference between metal parts of different velocity.
- Friction losses due to pressure difference across leakage paths.

The modified theory takes the effects of the gas-liquid mixture into consideration.

CALCULATION EXAMPLES

Dragster supercharger with methanol injection at the inlet

This is a dry screw compressor with synchronized rotors. The flow through the compressor is determined by the volume flow to the engine at which inlet it is mounted. In this case some of the methanol is injected before the inlet and some during the compression phase. The main purpose for doing this is to cool the gas at the inlet which leads to decreased density of the incoming air - thus increasing the mass flow through the compressor - and to cool the air into the engine, which decreases the inlet pressure to the engine, i.e. decrease in power consumption. As a secondary effect the housing and the rotors are also cooled, which results in smaller thermal deformations and consequently low leakage.

Assumptions:

- The injected methanol quantity is in liquid phase.
- The heat transfer between gas and methanol is so small compared to the methanol heat capacity that no evaporation takes place during the filling and compression phase.
- Once the discharge port opens, an efficient mixing starts, which increases the heat transfer so much that the liquid fully evaporates.
- The gas and the liquid mix totally in the leakage paths.
- The gas-liquid flow in the leakage paths is subsonic or sonic.

Comparisons with experiments and more detailed calculations show that the above assumptions are valid.

Fig. 2 shows the power consumption and the mass flow as a function of the built-in volume ratio V_i for a 236 mm supercharger operating with or without evaporation of methanol at the inlet respectively.

The diagram shows that the mass flow is much higher when the methanol is injected in such a way that full evaporation takes place before the inlet port closes. It also shows that the power consumption is optimized at V_i = 2.1., which is possible with the screw compressor. In this situation the Roots blower must operate with V_i = 1.0, which means a considerable increase of power consumption.

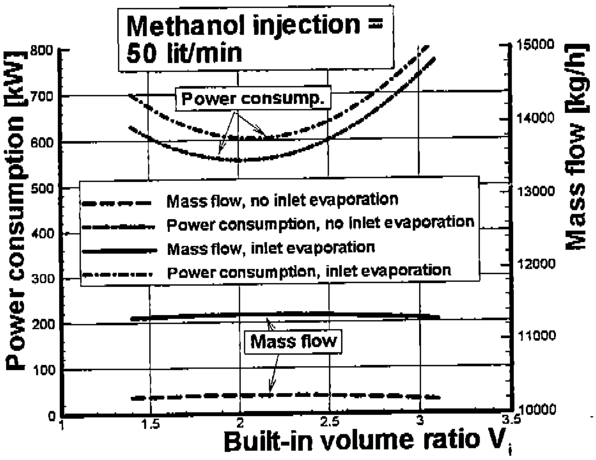

Fig. 2.
Influence of injected methanol at different built-in volume ratio V_i

Fig. 3 shows that the lowest boost pressure is obtained at optimized V_i, i e high boost presssure does not always mean an efficient supercharger - on the contrary it can mean a bad supercharger. As can be seen V_i = 1.0 gives a high boost pressure, which can mislead to the conclusion that it is efficient, when in actual fact it is not.

The reason for this boost pressure behaviour is that losses in efficiency, which means increased heat generation, convert into higher gas temperature and lower density. Since the screw compressor mass flow and the engine volume flow are constant it is then necessary to increase the boost pressure.

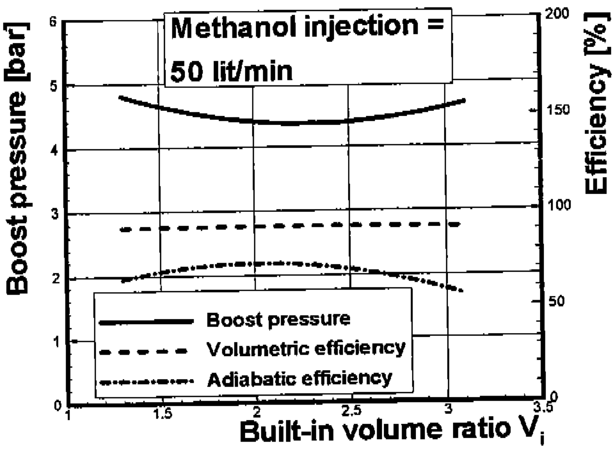

Fig. 3.
Influence of injected methanol at different built-in volume ratio V_i

Oil-free Screw Compressor with water injection at the inlet

In this case water is injected in front of the inlet of a dry screw compressor with synchronized rotors. Since this compressor operates at such high pressure ratio as 5.7 it is necessary to cool away the amount of heat generated by the gas compression. Otherwise it is very difficult to handle the metal deformations caused by the high temperatures.

The theoretical assumptions are similar to the methanol injected compressor.

Fig. 4 shows the discharge temperature and the efficiencies of a 642 mm male diameter screw compressor for process gas, with different contents of water in the inlet gas.

The diagram shows that the discharge temperature decreases very rapidly due to evaporation until saturation point is reached. It also shows that the temperature level for the saturation is higher for a case with high water partial pressure at the inlet than for a low one.

At 100 lit/min water injection rate the adiabatic efficiency has its optimum.

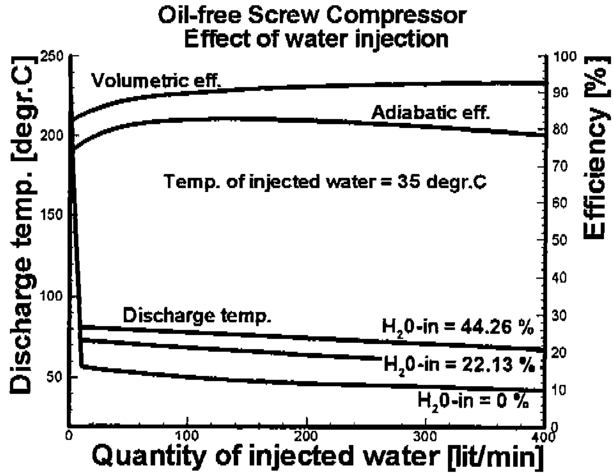

Fig. 4.
Influence of quantity of injected water

Refrigeration Screw Compressor

Presented examples are computer simulations of a refrigerant screw compressor operating with R134a at various P_d/P_s-ratios and a condensing temperature of 50°C.

In order to get an accurate theory it is necessary to split the total amount of injected oil flow into two separate flows, namely:

a) Flow that goes directly into the control volume after closure of the inlet port.

This is the main part of the total oil flow and the refrigerant that flashes out increases the driving torque since the inlet and the discharge ports are closed.

b) Flow to the low pressure bearing.

In this case the oil from the low pressure bearing goes to the compressor inlet. i.e. the refrigerant that flashes out from the oil goes to the inlet thus reducing the flow capacity. The influence on the driving torque is negligible.

Fig. 5 shows the calculated performance without any flashing from the refrigerant in the oil. It is very clear that the dissolved refrigerant decreases the performance greatly.

Fig. 6 shows the calculated performance with the low pressure bearing drainage to a closed control volume or to an open one.

As can be seen it is advantageous to drain the low pressure bearing to a closed thread.

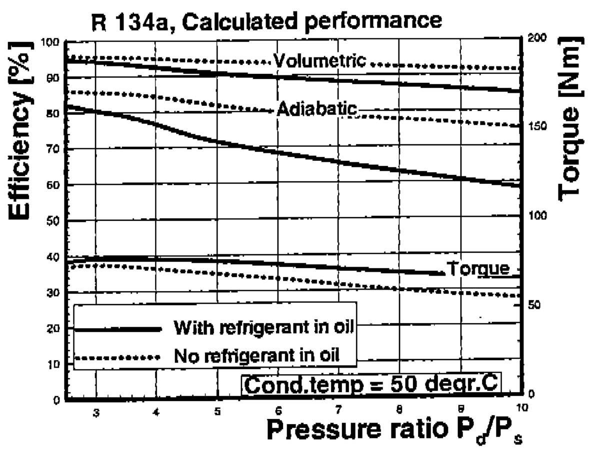

Fig. 5.
Influence of dissolved refrigerant in the oil.

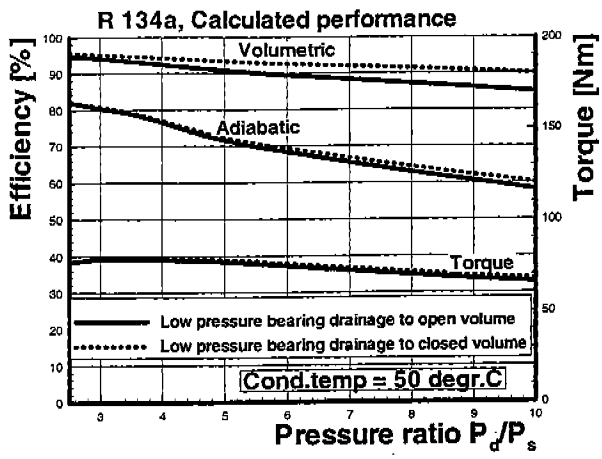

Fig 6.
Influence of low pressure bearing drainage arrangement.

CONCLUSIONS

A method for computer simulation of effects from injection of different liquids has been presented. The presented results show that this method is a valuable tool for analysies and deeper understanding of screw compressor performance.

The presented calculation examples have shown:

- Mass flow into dragster superchargers is improved if methanol is injected in such a way that evaporation takes place before the inlet port closes.
  Dragster boost pressure can be kept low since it is possible to run the screw compressor at optimum built-in volume ratio V_i. This is not possible for a Roots blower.
- Discharge temperatures after water injected screw compressors are strongly influenced by water evaporation. This effect can be misleading and make you believe that cooling during the compression is high.
- The dissolved refrigerant in the oil injected into refrigerant screw compressors decreases the performance considerably.
- It is advantageous to have the low pressure bearing drainage to a closed thread.

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