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J. A. McGovern
University of Dublin

S. Harte
Ford Motor Company

G. Strikis
Ford Motor Company

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Real Gas Performance Analysis of a Scroll or Rotary Compressor Using Exergy Techniques

James A. McGovern
University of Dublin
Trinity College, Dublin 2, Ireland

Shane Harte, Guntis Strikis
FORD Motor Company
Climate Control Division
Dearborn, MI 48120

Abstract:

The following paper further develops an analysis technique that uses the exergy (thermodynamic availability) of a gas to quantify the shaft power wastage in a compressor. First law techniques alone have serious limitations in the assessment of shaft power wastage. For instance the thermodynamic wastages due to throttling, friction or heat transfer with finite temperature differences are of practical significance, but are not properly quantified as wasted parts of the work by a first law analysis. Earlier work by the authors showed that exergy models were ideal for quantifying shaft power wastage when an accurate first law simulation model was available for a compressor. They used an ideal gas model in their previous analyses. However, the technique has now been successfully applied with a real gas model. Base equations are presented and results are given for how leakage, heat transfer, over/under compression (throttling), reexpansion volume and friction contribute to the overall power wastage in a scroll or rotary compressor.

Nomenclature:

- \( b \) specific flow exergy \((b=\text{h-PA.s})\) (joule/kg)
- \( h \) specific enthalpy (joule/kg)
- \( I \) exergy destruction (joule)
- \( m \) mass (kg)
- \( PA \) ambient pressure (Pa)
- \( Q \) heat transfer (joule)
- \( s \) specific entropy (joule/kgK)
- \( TA \) ambient temperature (K)
- \( T \) temperature (K)
- \( u \) specific energy (joule/kg)
- \( W \) work (joule)
- \( \text{SHC} \) specific heat capacity of oil (joule/kgK)
- \( \gamma \) specific volume \((m^3/kg)\)
- \( \text{\(\eta\)} \) exergy (availability) (joule)

Subscripts:
- \( \text{cv} \) gas in control volume
- \( e \) gas at outlet of isenthalpic orifice
- \( i \) gas at inlet of orifice
- \( \text{Press} \) due to pressure drop
- \( \text{TempMx} \) due to mixing of gases at different temperatures
- \( \text{HT} \) due to heat transfer
- \( \text{fr} \) due to mechanical friction
- \( \text{oil} \) of the oil
- \( \text{mix} \) due to mixing of gas or oil masses
- \( 1,2 \) condition of components before mixing
- \( \text{tot} \) condition of mixture
Introduction:

The concepts of entropy and exergy (availability) have been around for a long time. State of randomness, quality of energy, measure of order are all abstract terms widely used to define the concept of entropy. They tend to be obscure definitions leaving the eternally voiced question 'What is entropy?'. Exergy on the other hand is a more fathomable concept. The exergy of a substance is the maximum amount of useful work that can be derived from that substance in bringing it to an equilibrium state with the environment.

The technique that follows uses the concept of exergy to quantify the losses that occur in a compressor. A simple case shall be taken to illustrate the technique. There are two volumes of gas at different temperatures and pressures separated by a diaphragm. The diaphragm is punctured and the two gases mix together. We know intuitively that an irreversible process has occurred. How is this loss quantified?

A first law analysis fails us completely. Conservation of energy tells us that there is no energy loss.

If we use a second law analysis and the definition of exergy, the loss can be measured directly. As exergy is a co-property of the state of the gas and the environment, the exergies of the gas volumes before and after mixing can be quantified. The loss will be the reduction in total exergy of the system!

In this paper the same principle is used to quantify all the loss mechanisms in a compressor. For more information on the exergy analysis technique consult [2] or [3]. The losses in a compressor can be summarised as follows.

- Throttling at valves, orifices, bends
- Mechanical friction
- Leakage
- All heat transfers
- Reexpansion of compressed gases

Conventional methods of compressor analysis have tended to concentrate primarily on the friction and throttling losses ([4],[5]). Leakage, heat transfer, and re-expansion of compressed gases have tended to be lumped together as the deficit loss. A full breakdown of the losses can be achieved when the models described in this paper are used.

Without a doubt the exergy analysis technique is the thermodynamically correct way to analyse a compressor! However it does have its problems as you may find out when you attempt to apply it. Considerable experimental information is required! Mass flow rates, heat transfer rates, instantaneous pressures and temperatures... Does this mean we should not use it? The solution the authors have chosen is to create a simulation that predicts as accurately as can be experimentally measured the performance of the compressor.

The universality of the equations shown here also means that any of the equations can be applied on their own without reference to other simultaneous effects! For example taking a problem of heat transfer through a wall separating a discharge and suction plenum. If the heat flux, the temperatures of the suction and discharge gases are all known, you can tell exactly how much it affects your inefficiency by applying equation (4) following. You do not need to consider any other effect occurring in the compressor. Similarly
throttling, leakage, reexpansion losses can also be quantified separately if the relevant information is known.

**Compressor Simulation:**

As mentioned above an accurate model of the compressor is required. The components of the model are described here as follows. The model is based on a first law analysis of the compressor described in the short course Purdue manuals, [6], [7].

Gas Volumes: 1st law real gas volumes are assigned to the main plenums and volumes in the compressor.

Valves: Flow and force area models are used for these.

Heat Transfer: Heat transfer occurs between gas-metal, metal-metal, gas-oil and metal-atmosphere.

Friction: Friction occurs when surfaces contact at a given load, with a given relative velocity (experimental correlation used). Dissipation of friction heat was best approximated as a direct source of heat into the oil.

Oil: Oil influences leakage, friction and total specific heat capacity of the refrigerant-oil mixture. Oil in the model is seen as a parallel flow to the gas flow.

Heat expansion/Pressure: Relative expansion rates of the metal sections due to different materials and temperatures along with pressure deflections will affect the clearances/interferences in the compressor, ultimately affecting the friction and leakage. The compressor was split into simple linear models of the components of the compressor in the axial and radial directions.

Reexpansion volume: In most rotary compressors reexpansion volumes are common. In sliding vane compressors the port area around the valve contains a pocket of high pressure gas, this comes in contact with a lower pressure gas and there is an associated loss. In scroll compressors when the inbuilt compression ratio of the scroll compressing members do not match the system compression ratio, there is an analogous case of reexpansion loss. The model here assumes the two unmatched volumes are mixed instantaneously with mass and energy balance.

**Exergy Destruction Rates:**

As stated above the causes of wastage of shaft power utilisation can be pin-pointed exactly using the present technique. Following are the equations required to quantify how much extra shaft power is required to overcome the problem. The equations of state for R134a are taken from [8].

Throttling:

Throttling can itself be decomposed into two subgroups. In a normal throttling operation in a compressor the gas that is flowing goes from a higher pressure to a lower pressure, once the pressure of the gas has been equalised the temperatures of the inlet gas and plenum gas must equalise. The losses associated with the pressure drop and the losses associated with the gases mixing are as follows.
The above equations (1) and (2) can be used to quantify the losses for flow from any given volume to another, irrespective of path. Therefore the equations defined above were used to calculate conventional throttling losses such as through valves, and also to quantify leakage losses. The mechanism of loss is identical for both cases.

The equations above can be combined to form the following equation for the whole throttling process (this prevents the user having to determine the intermediate condition denoted by the subscript $\varepsilon$ above).

\[
\dot{I}_{\text{th}} = \dot{m} TA \cdot \frac{(s_{cv} - s_{\varepsilon}) - (h_{cv} - h_{\varepsilon})}{T_{cv}}
\]

(3)

Heat Transfer:

Whenever there is heat transfer across a finite temperature difference there will be an associated loss. Conceptually the loss is as follows. The higher the temperature of a heat source from atmospheric temperature, the greater its potential to do mechanical work (according to the Carnot heat engine). Therefore if there is heat transfer, energy goes to a lower temperature with an associated loss in exergy. For all heat transfer paths, irrespective of source and sink material, the loss can be quantified as follows,

\[
\dot{I}_{\text{th}} = \dot{Q} TA \cdot \frac{1}{T_{\text{low}}} - \frac{1}{T_{\text{high}}}
\]

(4)

Friction:

Along the same lines, the conventional wisdom states that all friction heat is wasted shaft power. According to the exergy technique however this is not the case. As argued above, the friction energy is dissipated to the oil or the metal of the compressor heating them up. By the action of heating the oil or metal, their respective exergies increase. Therefore the losses associated with friction are as follows,

\[
\dot{I}_{\text{fr}} = \dot{W}_{fr} \cdot \frac{1}{T_{\text{coll}} - TA} / T_{\text{coll}}
\]

(5)

Reexpansion Volume:

When two volumes of gas mix thoroughly the irreversibility is the difference between the total exergy of the two volumes before mixing minus the total exergy of the mixture after mixing.

\[
I_{\text{mix}} = \Xi_1 + \Xi_2 - \Xi_{\text{tot}}
\]

(6)

where the exergy of a stationary gas volume is as follows,

\[
\Xi = m'(u + PAv - TA's)
\]

(7)

Another case where we require the use of the equation (6) is when oil flows from one volume to the next. The following case is particular to the model assumed. As stated above the oil is assumed to be in parallel flow with the gas, the only interaction between the gas and the oil being heat transfer in the volume. In reality the oil will not mix with the oil in the volume but will be heated directly by the gas. For us to be consistent with the model however we must calculate the losses according to the way they are generated...
by the model. Therefore a requirement is that we know the exergy of oil at a
given temperature above ambient. The equation is as follows,

\[ \Xi = \dot{m} \cdot H - (T_o - T_A + \ln (T_A / T_o)) \]  

Exergy Balance:

When all the losses generated by the equations above are totalled up,
there should be an exergy balance across the compressor. In other words, over
a given steady state cycle, pure exergy in the form of shaft power should
equal 1) the exergy difference between the fluid entering and leaving the
compressor and 2) the sum of the exergy losses occurring within the compressor.
A correction has to be made if the cycle is not steady state, the exergy that
is stored or released from the control volume analysed must also be accounted
for.

\[ \dot{\omega} = \dot{h} \cdot T_A \cdot (b_{dch} - b_{suct}) + \sum \dot{f}_{\text{Press}} + \sum \dot{f}_{\text{Temp}} + \sum \dot{f}_{\text{Fr}} + \sum \dot{f}_{\text{Mix}} + \sum \dot{f}_{\text{TH}} \]  

Analysis Results:

The simulation model of the compressor was used to provide the input
data for the exergy analysis. The program itself is validated against
experimental results. Experimental information for mass flow, suction and
discharge states (temperature and pressure), oil flow, horsepower, body
temperature and pressures and temperatures at points in the compression cycle
were used to validate the simulation results. Despite all these measurements
some correlation and prediction was still required.

The following results are representative of the relative proportions of
the loss making regimes in a compressor.

<table>
<thead>
<tr>
<th>RPM</th>
<th>Overall Shaft Power Input</th>
<th>Watts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1681</td>
<td></td>
</tr>
<tr>
<td>Losses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Throttling at valves/orifices (pressure)</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Mixing after throttling (temperature)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Leakage (pressure and temp)</td>
<td>163</td>
<td></td>
</tr>
<tr>
<td>Friction</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Heat transfer</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>Heat transfer (gas-oil)</td>
<td>.2</td>
<td></td>
</tr>
<tr>
<td>Mixing of the oil</td>
<td>.6</td>
<td></td>
</tr>
<tr>
<td>Reexpansion Volume</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>Total Losses</td>
<td>398</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>76% ((-1-398/1681))</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RPM</th>
<th>Overall Shaft Power Input</th>
<th>Watts</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>7116</td>
<td></td>
</tr>
<tr>
<td>Losses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Throttling at valves/orifices (pressure)</td>
<td>3300</td>
<td></td>
</tr>
<tr>
<td>Mixing after throttling (temperature)</td>
<td>111</td>
<td></td>
</tr>
<tr>
<td>Leakage (pressure and temp)</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Friction</td>
<td>1406</td>
<td></td>
</tr>
<tr>
<td>Heat transfer</td>
<td>130</td>
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</tr>
<tr>
<td>Heat transfer (gas-oil)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Mixing of the oil</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Reexpansion Volume</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>Total Losses</td>
<td>3411</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>52% ((-1-3411/7116))</td>
<td></td>
</tr>
</tbody>
</table>
As can be seen above the majority of the efficiency losses that occur in the compressor are due to throttling, leakage and friction. However the losses due to heat transfer are quite appreciable as also the losses due to reexpansion and the method shown in this paper is the only accurate way to quantify these losses specifically.

Conclusions:

The exergy method of compressor analysis has been further developed in this paper. The method has been shown to provide very detailed information on the loss mechanisms within a compressor. It was shown how the models could be incorporated in an existing first law model, or else how the models could be used individually where appropriate experimental information is known.

References:
6) Soedel, W., 'Introduction to Computer Simulation of Positive Displacement Type Compressors', Short Course Notes, Purdue Univ., W. Lafayette, Indiana, USA, 1972.