PERFORMANCE OF A SMALL-SCALE ORGANIC RANKINE CYCLE SYSTEM USING A REGENERATIVE FLOW TURBINE: A SIMULATION ANALYSIS

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Introduction

Model

Results

Conclusions

2 main flows

- Tangential (Q)
- Circumferential (Qm)

Main stream

Transfer momentum from blades to main steam

Cause of loss and low efficiency

Present RFT prototype

Channel

Impeller

Q

Qm
A low cost, reliable expander for small-scale ORC units?

A possibility is introduced here: Regenerative flow (RF) turbo-machines, also known with other names such as peripheral, side channel, tangential, vortex, and turbulence turbo-machines.

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**Advantages**
- High heads in low flow rates
- Low speeds
- Can work with highly variable flow rates
- Can work with 2-phase flow
- Low maintenance
- Low cost
- Compact & reliable

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**RF turbo-machines**

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**disadvantages**
- Low Efficiency

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suitable for lubrication, control, filtering and booster systems

suitable for vehicles, gas pipelines

suitable to operate with hot or volatile liquids as pump, or in small-scale cryogenic cycles as compressors

suitable for small-scale plants

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Normalized dimensions of the RFT

<table>
<thead>
<tr>
<th>D/W</th>
<th>R1/W</th>
<th>R2/W</th>
<th>r2/W</th>
<th>r1/W</th>
<th>((\pi D_m)/(n \cdot W))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.388</td>
<td>1.292</td>
<td>2.292</td>
<td>0.5</td>
<td>0.5</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Geometry of CFD

Experimental apparatus (a and b) [1], and 3D model (c and d)

Simulation of RFT with air

Assumptions:
- Steady state
- Ideal gas density model
- Sutherland three-coefficient model for viscosity
- Negligible axial and radial leakage
- Adiabatic machine

CFD Model:
- RSM_BSL model
- MRF model (Frozen Rotor)
- Pressure-velocity coupling scheme: PISO
- Pressure discretization scheme: PRESTO!
- Inlet BC: Mass flow & Temperature
- Outlet BC: Pressure & Temperature

0.5 mm thickness (18 node/mm)

Variation of the outlet temperature with mesh density
Model Validation with experimental data [1] (air)

Comparison of outlet temperature (left) and isentropic efficiency (right) between CFD results and experimental data [1].

Flow Visualization (air)

Velocity vectors in a typical cross section plane in the channel

Iso-pressure surfaces

Streamlines colored by the total temperature of the flow

a) position of sample points along the channel, b) Variations of total pressure along the channel at 3000 RPM (BM=0.08) and different flow rates
Simulation of RFT with **R245fa**

Same geometry, mesh and model settings of the model with air, except for density:
- Peng-Robinson real gas model for density
- BC temperature and pressures similar to a typical ORC unit
- The range of the mass flow rate is determined from CFD results of the RFT considering the maximum suction pressure 20 bar (equivalent of PR of about 6.5)

**Boundary conditions of the CFD model**

<table>
<thead>
<tr>
<th>Inlet BCs</th>
<th>Outlet BCs</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass flow (kg/s)</strong></td>
<td><strong>Temperature °C</strong></td>
<td><strong>Pressure (bar)</strong></td>
</tr>
<tr>
<td>0.3-0.9</td>
<td>120</td>
<td>3</td>
</tr>
</tbody>
</table>

Total-to-static isentropic efficiency

\[ \eta_{t,s} = \frac{W_{act}}{W_{is}} = \frac{(h_{01}-h_{02})}{(h_{01}-h_{2s})} \]
Simulation of RFT with **R245fa**

**Total pressure ratio (PR)**

- Linear increase of PR with mass flow rate
- The PR is higher at the lower rotational speed, in contrast to traditional turbines → due to void effect in the channel

**Output power**

- The power of the RFT increases almost linearly with an increment of the mass flow rate up to a certain point

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The total pressure ratio by the mass flow rate in different RPMs

Output Power by mass flow rate in different RPMs
Simulation of RFT with **R245fa**

**Total-to-static isentropic efficiency**

- Relatively low isentropic efficiency compared to commercially available positive displacement expanders or dynamic turbines
- Higher isentropic efficiency working with R245fa compared to air → due to higher molecular weight of R245fa → weaker swirl → less losses

![Graph showing isentropic efficiency by mass flow rate (R245fa)](image1)

![Graph showing isentropic efficiency by mass flow rate (Air)](image2)

Streamlines colored by the total temperature at 6000 RPM & $\dot{m} = 0.3 \text{ kg/s}$ for R245fa and air
The entropy loss coefficient is a non-dimensional number representing the loss in the isentropic efficiency. For the sake of comparison, the relative entropy loss coefficient has been used, which is the $\zeta$ calculated in each zone divided to the total $\zeta$ calculated from the inlet boundary of the RFT to the outlet plane.

\[
\zeta = \frac{T_2 \Delta s}{h_{02} - h_2}
\]

Relative entropy loss coefficient in three zones at 3000 RPM (BM=0.08) & 0.3 kg/s ($\dot{m}=0.054$)
Simulation of ORC with R245fa

The temperature difference between the inlet of the cooling fluid and the saturation temperature of the organic working fluid in the condenser is considered 25 °C. The mass flow rate of the R245fa is an input to the model whilst the isentropic efficiency of the RFT and its pressure ratio (PR) are obtained from the CFD results. Minimum allowable temperature pinch is assumed 10 °C for both evaporator and condenser

Temperature distribution in the heat exchangers of the ORC unit at $\dot{m} = 0.8$ kg/s, $P_{\text{cond}} = 2.94$ bar & $P_{\text{evap}} = 12$ bar

Performance of the ORC system

<table>
<thead>
<tr>
<th>$m_{\text{ORC}}$ = 0.6 kg/s</th>
<th>$m_{\text{ORC}}$ = 0.8 kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{evap}}$</td>
<td>9 bar</td>
</tr>
<tr>
<td>$W_{\text{pump}}$</td>
<td>0.39 kW</td>
</tr>
<tr>
<td>$W_{\text{RFT},el}$</td>
<td>4.69 kW</td>
</tr>
<tr>
<td>$\eta_{\text{net},el}$</td>
<td>3.2 %</td>
</tr>
</tbody>
</table>

Design parameters of the ORC system

<table>
<thead>
<tr>
<th>Organic Fluid</th>
<th>R245fa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump isentropic efficiency</td>
<td>75%</td>
</tr>
<tr>
<td>Pump mechanical efficiency</td>
<td>96%</td>
</tr>
<tr>
<td>Electrical generator efficiency</td>
<td>97%</td>
</tr>
<tr>
<td>Sub-cooling at the pump inlet</td>
<td>5 °C</td>
</tr>
<tr>
<td>Super-heating in the evaporator</td>
<td>10 °C</td>
</tr>
</tbody>
</table>
The PR of the RFT decreases with RPM, thus confirming the peculiarity of this type of expander.

The isentropic efficiency of the RFT achieves a peak of more than 45%, explained via a less swirl showed in the CFD results has been found.

The output power increases with the mass flow rate almost linearly, but up to a certain limit.

The net electrical efficiency of the ORC unit is around 3%, at the highest RPM of the RFT.

The range of the mass flow rate that can be elaborated by the RFT is higher than the one with volumetric expanders but its isentropic efficiency, despite being increased using R245fa, is still low.

Low manufacturing costs and high reliability of RFTs can be highlighted further compared to turbo-machines working in this range of mass flow rates. Nevertheless, a re-engineering of the design of the RFT must still be performed to reduce the main losses, especially the leakage flow through the clearance gap between the stripper body and blade tips.

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