# The Benefit of Variable-Speed Turbine Operation for Low-Temperature Thermal Energy Power Recovery

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# Motivation for this Study

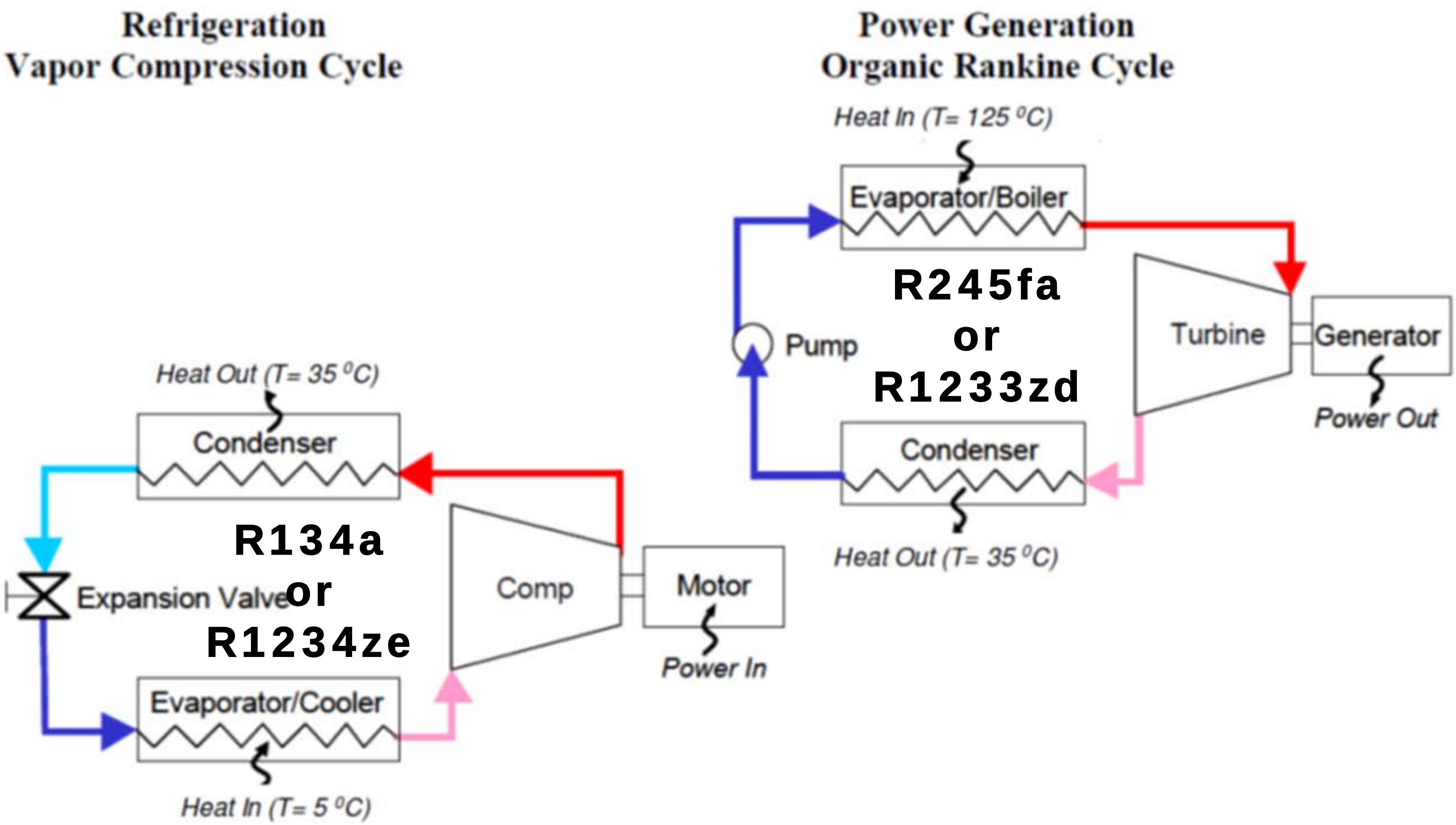
It is well know that:

- Variable speed compressor operation reduces annual electricity consumption of a centrifugal chiller by up to 40% compared to fixed-speed operation

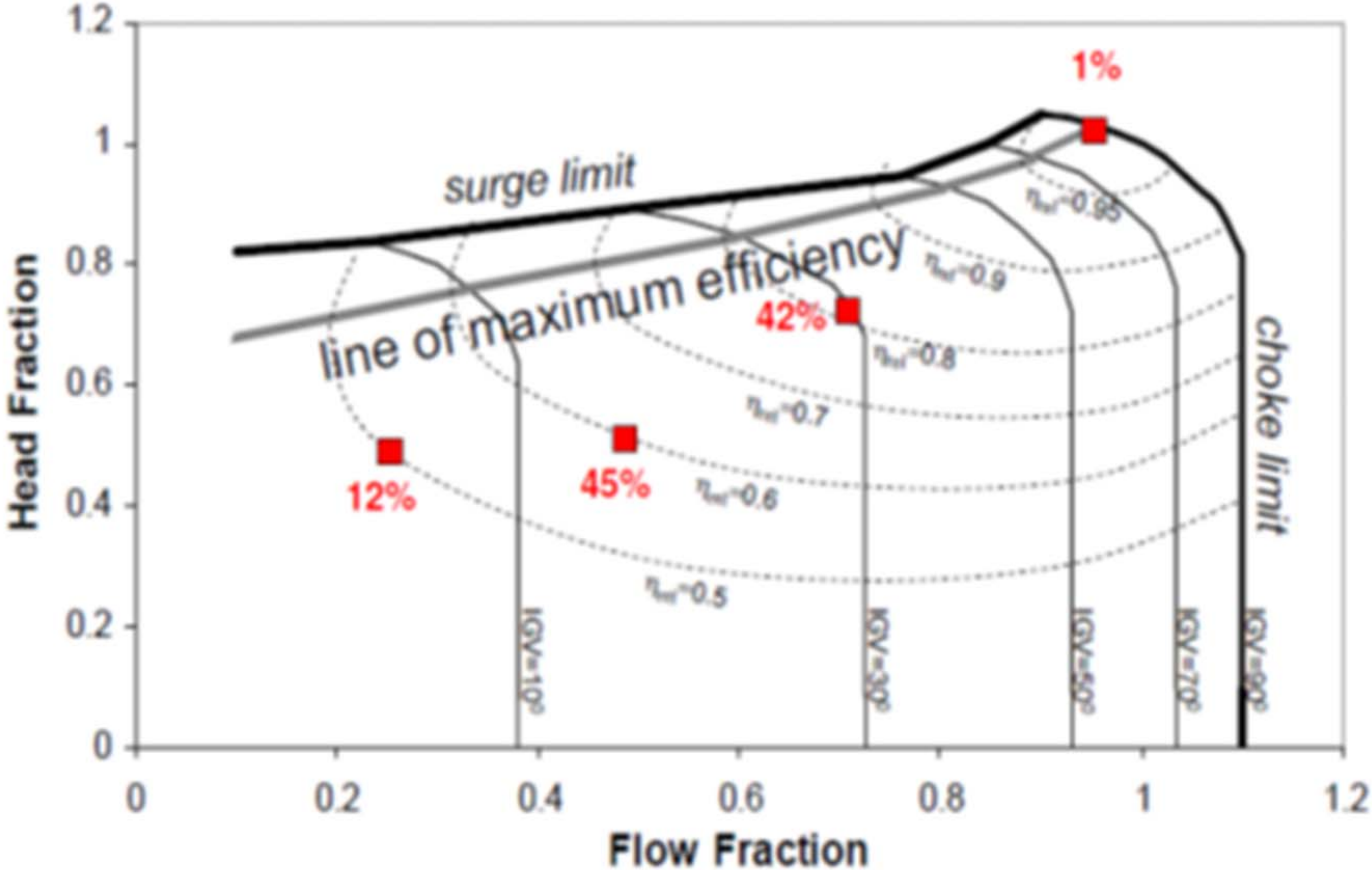
Question to be answered in this study:

- How much is the benefit of variable speed power conversion for low-temperature ORC turbines?

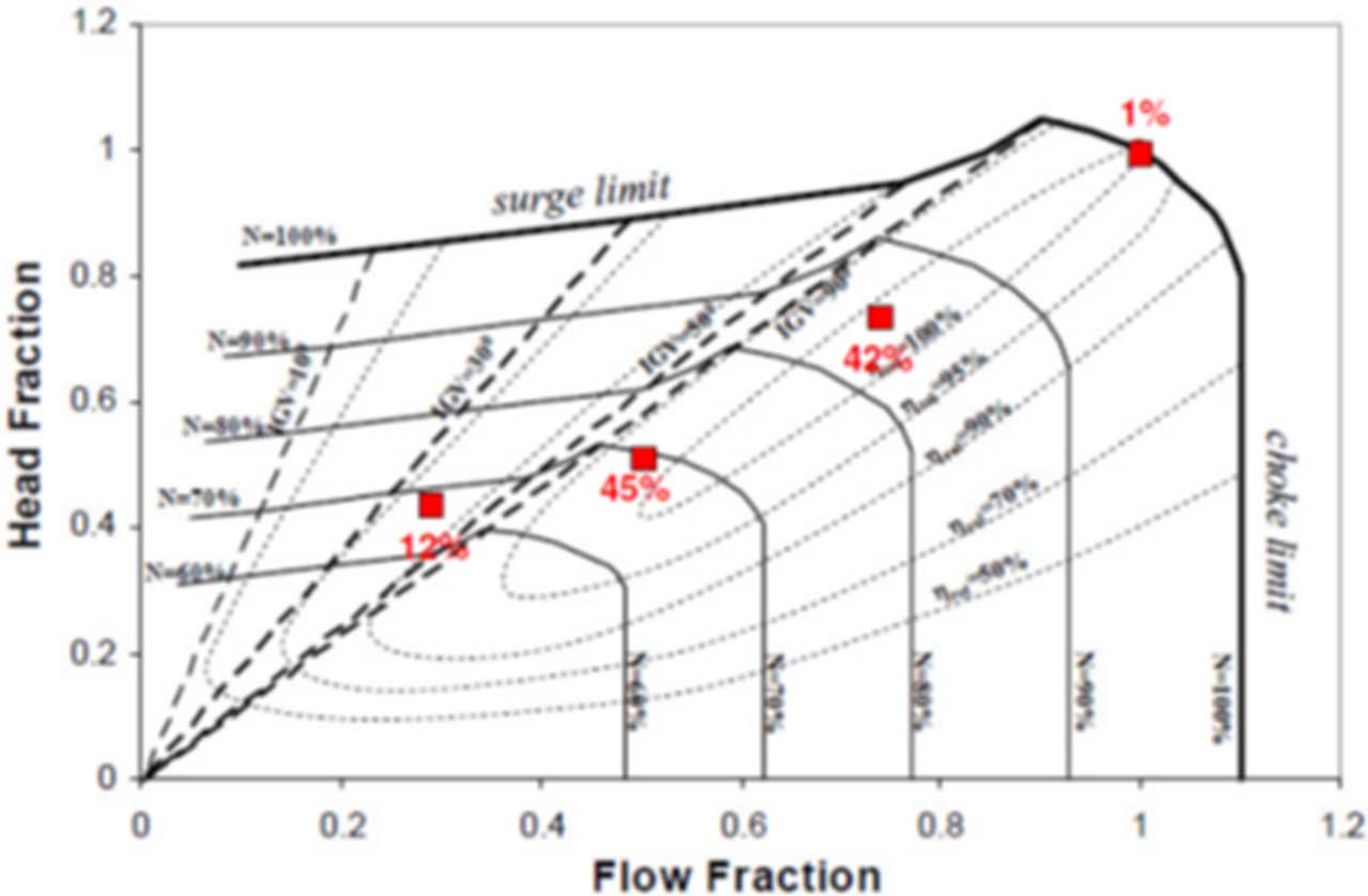
# Vapor Compression versus Organic Rankine Cycle



# Fixed–Speed Centrifugal Compressor Map



# Variable–Speed Centrifugal Compressor Map



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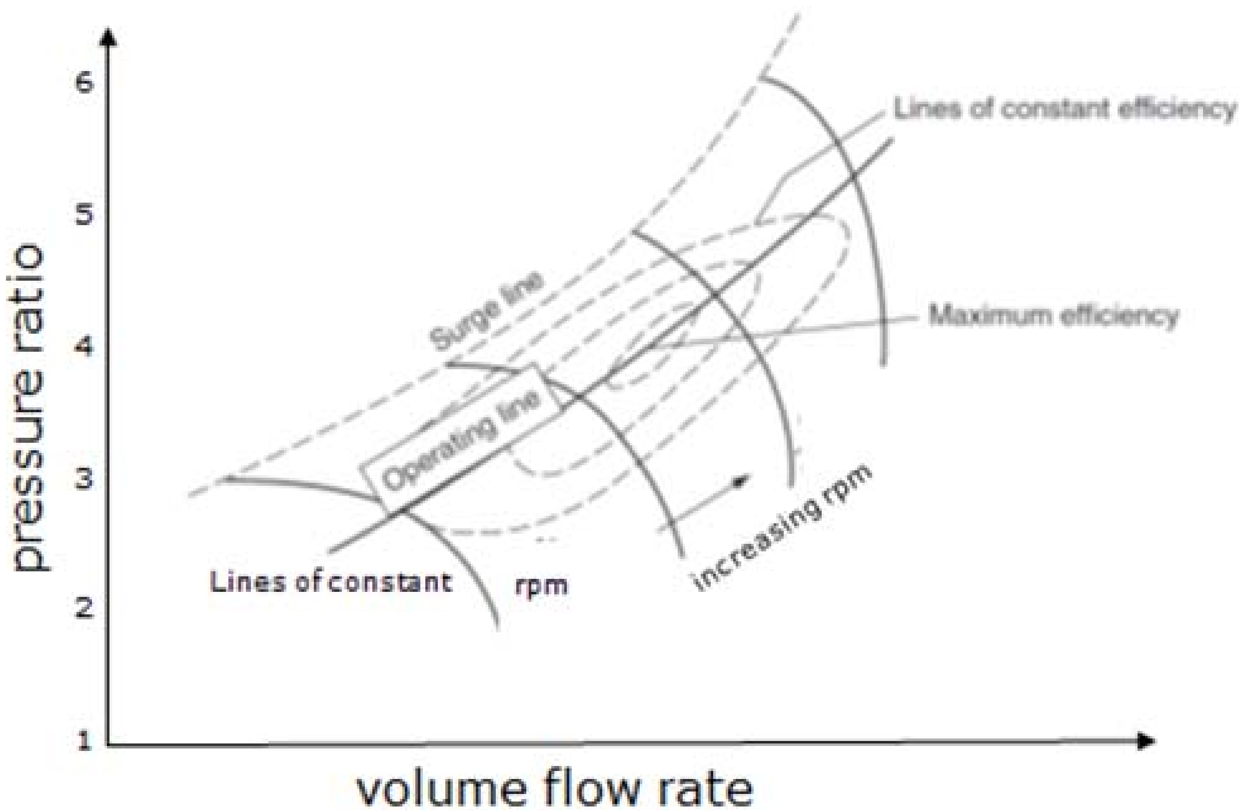
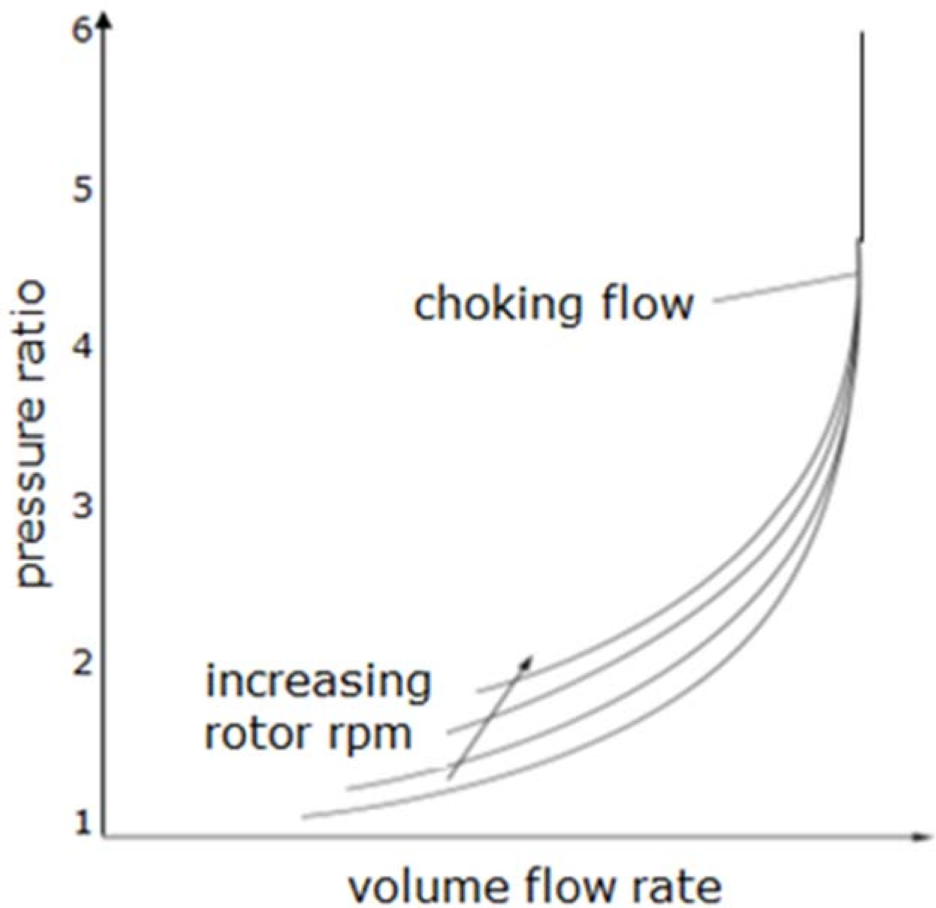


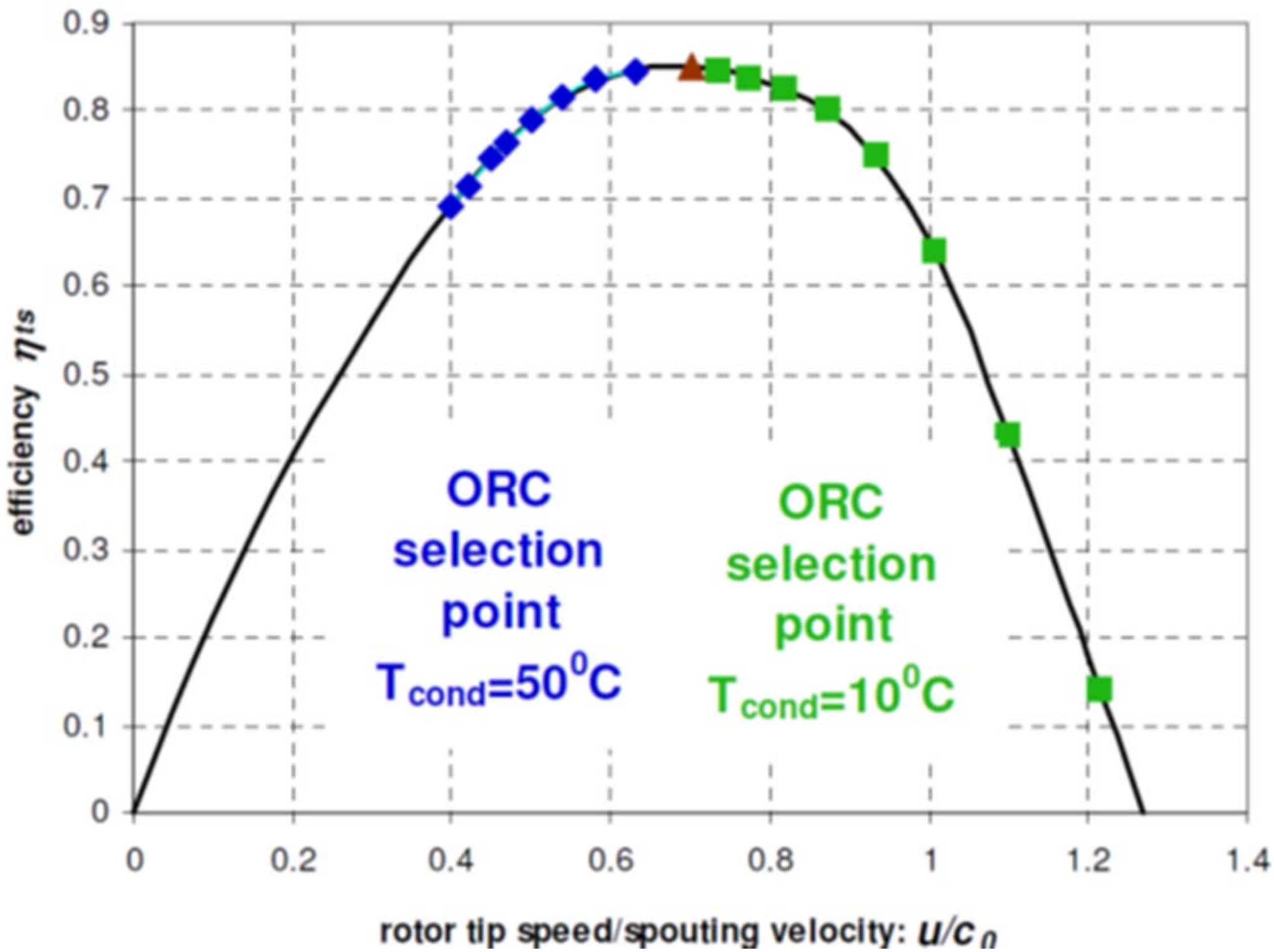

*Higher speed always increases max capacity*
*Best efficiency is always achieved close to surge*

# Variable–Speed Radial Inflow Turbine Map




*Speed does not affect maximum capacity*
*Efficiency is only affected by speed at higher pressure ratio*

# Turbine efficiency as a function of $u/c_0$



## $\eta_{turbine}(T_{sat,cond})$ when $T_{sat,cond,design} = 50\ ^0C$

| $T_{sat,cond}$ | $P_{sat,cond}$ | $T_{sat,evap}$ | $P_{sat,evap}$ | $\Delta h_{is}$ | $c_0$ | u | $u/c_0$ | $\eta_{turbine}$ |
|---|---|---|---|---|---|---|---|---|
| $^0C$ | kPa | $^0C$ | kPa | kJ/kg | m/s | m/s | - | - |
| 10 | 83 | 75 | 695 | 38.80 | 279 | 114 | 0.41 | 0.70 |
| 15 | 102 | 75 | 695 | 35.17 | 265 | 114 | 0.43 | 0.74 |
| 20 | 124 | 75 | 695 | 31.65 | 252 | 114 | 0.45 | 0.77 |
| 25 | 149 | 75 | 695 | 28.25 | 238 | 114 | 0.48 | 0.79 |
| 30 | 179 | 75 | 695 | 24.97 | 223 | 114 | 0.51 | 0.81 |
| 35 | 213 | 75 | 695 | 21.78 | 209 | 114 | 0.55 | 0.82 |
| 40 | 252 | 75 | 695 | 18.71 | 193 | 114 | 0.59 | 0.83 |
| 45 | 296 | 75 | 695 | 15.74 | 177 | 114 | 0.64 | 0.84 |
| 50 | 345 | 75 | 695 | 13.35 | 163 | 114 | 0.70 | 0.84 |

## $\eta_{turbine}(T_{sat,cond})$ when $T_{sat,cond,design} = 10\ ^0C$

| $T_{sat,cond}$ | $P_{sat,cond}$ | $T_{sat,evap}$ | $P_{sat,evap}$ | $\Delta h_{is}$ | $c_0$ | u | $u/c_0$ | $\eta_{turbine}$ |
|---|---|---|---|---|---|---|---|---|
| $^0C$ | kPa | $^0C$ | kPa | kJ/kg | m/s | m/s | - | - |
| 10 | 83 | 75 | 695 | 38.80 | 279 | 195 | 0.70 | 0.84 |
| 15 | 102 | 75 | 695 | 35.17 | 265 | 195 | 0.74 | 0.83 |
| 20 | 124 | 75 | 695 | 31.65 | 252 | 195 | 0.78 | 0.82 |
| 25 | 149 | 75 | 695 | 28.25 | 238 | 195 | 0.82 | 0.81 |
| 30 | 179 | 75 | 695 | 24.97 | 223 | 195 | 0.87 | 0.8 |
| 35 | 213 | 75 | 695 | 21.78 | 209 | 195 | 0.93 | 0.74 |
| 40 | 252 | 75 | 695 | 18.71 | 193 | 195 | 1.01 | 0.63 |
| 45 | 296 | 75 | 695 | 15.74 | 177 | 195 | 1.10 | 0.45 |
| 50 | 345 | 75 | 695 | 13.35 | 163 | 195 | 1.19 | 0.22 |

# Fixed-speed seasonal turbine efficiency drop for a 10 $^0$C design point

| $T_{sat,cond}$ | $f_{ambient}$ | $\Delta h_{is}$ | $f_{\Delta his}$ | $f_{ambient}$ * $f_{\Delta h,is}$ | $f_{normalized}$ | $\eta_{turbine}$ | $f_{normalized}$ * $\eta_{turbine}$ |
|---|---|---|---|---|---|---|---|
| $^0$C | - | kJ/kg | - | - | - | - | |
| 10 | 0.02 | 38.80 | 0.170 | 0.003 | 0.031 | 0.84 | 0.026 |
| 15 | 0.06 | 35.17 | 0.154 | 0.009 | 0.084 | 0.83 | 0.070 |
| 20 | 0.12 | 31.65 | 0.139 | 0.017 | 0.151 | 0.82 | 0.124 |
| 25 | 0.18 | 28.25 | 0.124 | 0.022 | 0.202 | 0.81 | 0.164 |
| 30 | 0.24 | 24.97 | 0.109 | 0.026 | 0.238 | 0.80 | 0.191 |
| 35 | 0.18 | 21.78 | 0.095 | 0.017 | 0.156 | 0.74 | 0.115 |
| 40 | 0.12 | 18.71 | 0.082 | 0.010 | 0.089 | 0.63 | 0.056 |
| 45 | 0.06 | 15.74 | 0.069 | 0.004 | 0.038 | 0.45 | 0.017 |
| 50 | 0.02 | 13.35 | 0.058 | 0.001 | 0.011 | 0.22 | 0.002 |
| Total | 1.00 | 228.42 | 1.000 | 0.110 | 1.000 | | 0.765 |

**assumed frequency for ambient conditions**

# Fixed-speed seasonal turbine efficiency drop for a 50 $^0$C design point

| $T_{sat,cond}$ $^0$C | $f_{ambient}$ - | $\Delta h_{is}$ kJ/kg | $f_{\Delta his}$ - | $f_{ambient}$ * $f_{\Delta h,is}$ - | $f_{normalized}$ - | $\eta_{turbine}$ - | $f_{normalized}$ * $\eta_{turbine}$ |
|---|---|---|---|---|---|---|---|
| 10 | 0.02 | 38.80 | 0.170 | 0.003 | 0.031 | 0.69 | 0.021 |
| 15 | 0.06 | 35.17 | 0.154 | 0.009 | 0.084 | 0.72 | 0.060 |
| 20 | 0.12 | 31.65 | 0.139 | 0.017 | 0.151 | 0.75 | 0.113 |
| 25 | 0.18 | 28.25 | 0.124 | 0.022 | 0.202 | 0.77 | 0.156 |
| 30 | 0.24 | 24.97 | 0.109 | 0.026 | 0.238 | 0.79 | 0.188 |
| 35 | 0.18 | 21.78 | 0.095 | 0.017 | 0.156 | 0.82 | 0.128 |
| 40 | 0.12 | 18.71 | 0.082 | 0.010 | 0.089 | 0.83 | 0.074 |
| 45 | 0.06 | 15.74 | 0.069 | 0.004 | 0.038 | 0.84 | 0.032 |
| 50 | 0.02 | 13.35 | 0.058 | 0.001 | 0.011 | 0.84 | 0.009 |
| Total | 1.00 | 228.42 | 1.000 | 0.110 | 1.000 | | 0.782 |

**assumed frequency for ambient conditions**

# CONCLUSIONS

- The change in cycle efficiency with ambient conditions affects the annual energy consumption of air-conditioning equipment as well as the annual energy production of low temperature ORC equipment.

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- The change in cycle efficiency with ambient conditions affects the annual energy consumption of air-conditioning equipment as well as the annual energy production of low temperature ORC equipment.
- The benefit of variable-speed centrifugal compressor operation for air-conditioning equipment (water- and air-cooled chillers) over fixed-speed operation on annual power consumption is known to be almost 40%.
- Variable speed turbine operation can improve the annual electricity production of low temperature ORC systems by up to 10% relative to fixed speed turbine operation, allowing maximum utilization of low temperature heat sources for ORC systems that have their full-load selection point at lower ambient temperatures.

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- The benefit of variable speed turbine operation for ORC systems is less than that of variable speed centrifugal compressor operation for refrigeration systems as a result of the larger head variation experienced by air-conditioning equipment and the stronger sensitivity of compressor efficiency for the same relative variation in head.

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- The benefit of variable speed ORC turbines diminishes for higher temperature ORC systems when the relative changes in head with variations ambient temperature become smaller.