POLITECNICO DI MILANO





THE CHOICE OF WORKING FLUID:

THE MOST IMPORTANT STEP FOR A SUCCESSFUL ORGANIC RANKINE CYCLE

(AND AN EFFICIENT TURBINE)

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The key messages of this lecture

- the choice of the working fluid is the most relevant degree of freedom in the design of ORC
- The turbine is the most critical component of ORC, it plays a fundamental role in system performance, as well as in system cost
- There is a strong relationship between the working fluid properties and the turbine architecture (speed of revolution, number of stages, dimensions) and performance (isentropic efficiency)
- The working fluid selection must account for its consequences on the turbine design
- There are several peculiarities of ORC turbines, if compared to conventional (gas, steam) turbines:
  - The overall specific expansion work (kJ/kg) is much lower: it can be handled in few stages, at relatively low peripheral speeds
  - The adoption of transonic/supersonic flows is generally mandatory
  - A large variety of solutions (axial or radial inflow single stage, multi-stage axial, outflow or mixed radial/axial) can be adopted

Outline of the lecture

- Brief summary of working fluid selection criteria
  - General characteristics
  - The most relevant thermodynamic properties
  - Power cycle configurations
- The most important parameters affecting the turbine efficiency:
  - Stage specific speed
  - Volume ratio
  - Size parameter
- A new general correlation for preliminary (but quite accurate!) prediction of the turbine isentropic efficiency
- Some examples of ORC turbines successfully designed in the last 35 (!) years

General (evident) criteria for working fluid selection

The working fluid should be:

Requirements shared with the refrigerating and air-conditioning industry

- commercially available (low specific cost, large quantity)
- Non-flammable
- Non-toxic
- environmental benign (low ODP, low GWP)
- compatible with materials (elastomers, metals,…)
- …….
- …….

A specific requirement for ORC

- thermally stable

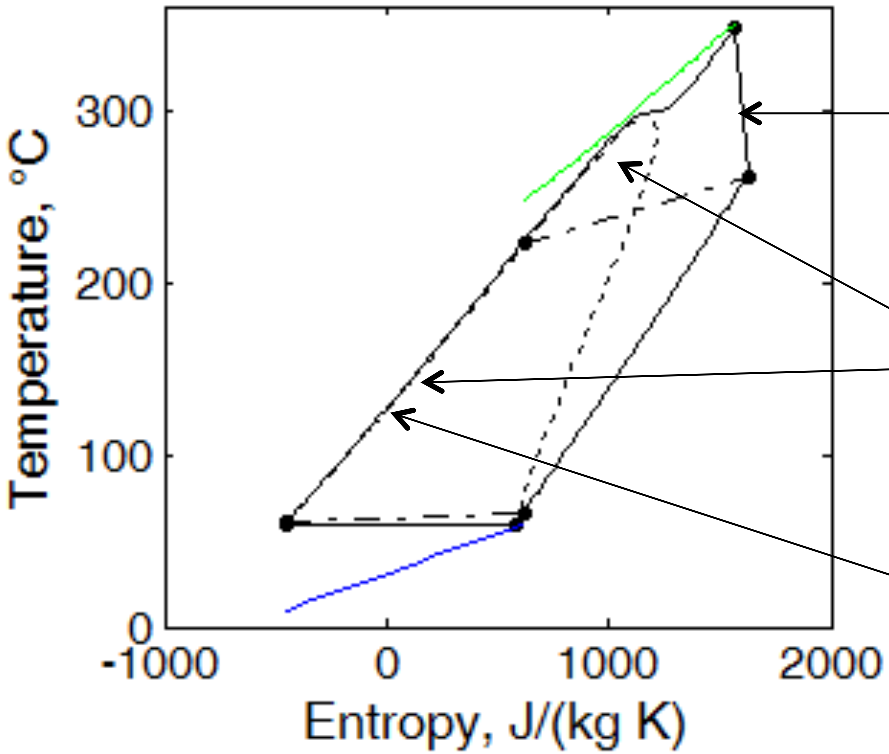
Some of the above requirements may not be fulfilled, especially for high temperature applications

Thermodynamic criteria for working fluid selection

Relevant properties:

- Molecular complexity (number of atoms per molecule): influences the “shape” of the Andrews curve and power cycle. Complex molecules cause:
  - “dry” expansion ☺
  - large fractions of heat input at variable temperature ☺
  - small temperature drops in the expansion phase ☹
  - large recuperators required ☹

Supercritical cycle with highly complex working fluid



“dry” expansion,
small temperature drop

Variable temperature
heat input

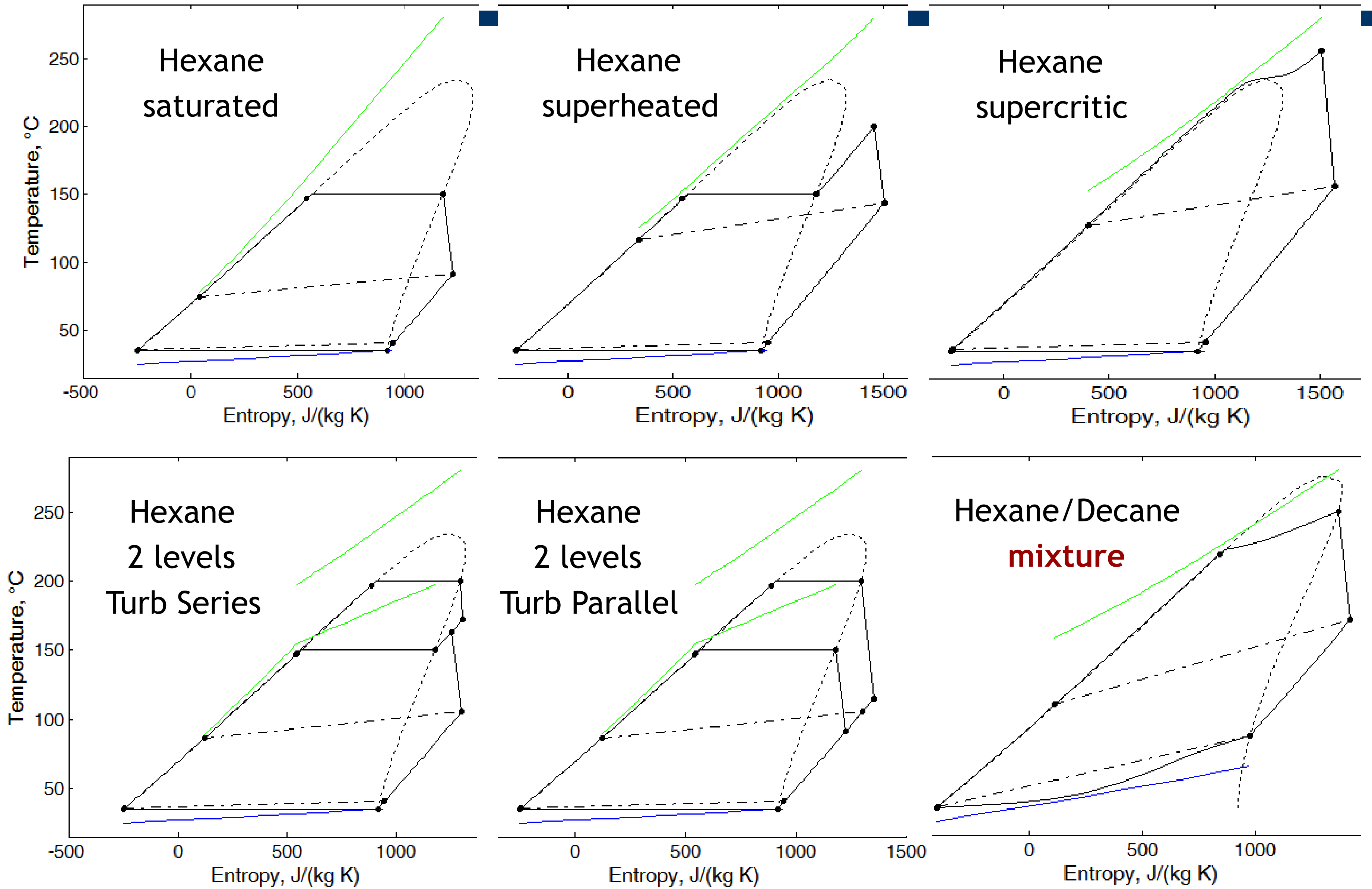
large recuperators
required

Thermodynamic criteria for working fluid selection

Relevant properties:

- Molecular complexity (number of atoms/molecule): influences the "shape" of the power cycle.
- Molecular mass. Heavy molecules cause:
  - small enthalpy drop during expansion ☺ ☺
  - poor heat transfer coefficients ☹
- Critical temperature:
  - fundamental choice to match the heat source and sink characteristics
  - condensation pressure: relevant for dimensions (and cost) of turbine and heat exchangers
- Pure fluid or mixture??
  - the presence of a *glide* (evaporation and condensation at variable temperature) could be advantageous for variable temperature heat sources and sinks

A large variety of cycle configurations



Turbine Design

- According to similarity rules, the efficiency of a turbine stage is primarily set by its specific speed and specific diameter

$$Ns = RPS\,\sqrt{V_{out,is}}\,/\Delta h_{is}^{3/4} \qquad Ds = Dm\,/\sqrt{V_{out,is}}\,/\Delta h_{is}^{1/4}$$

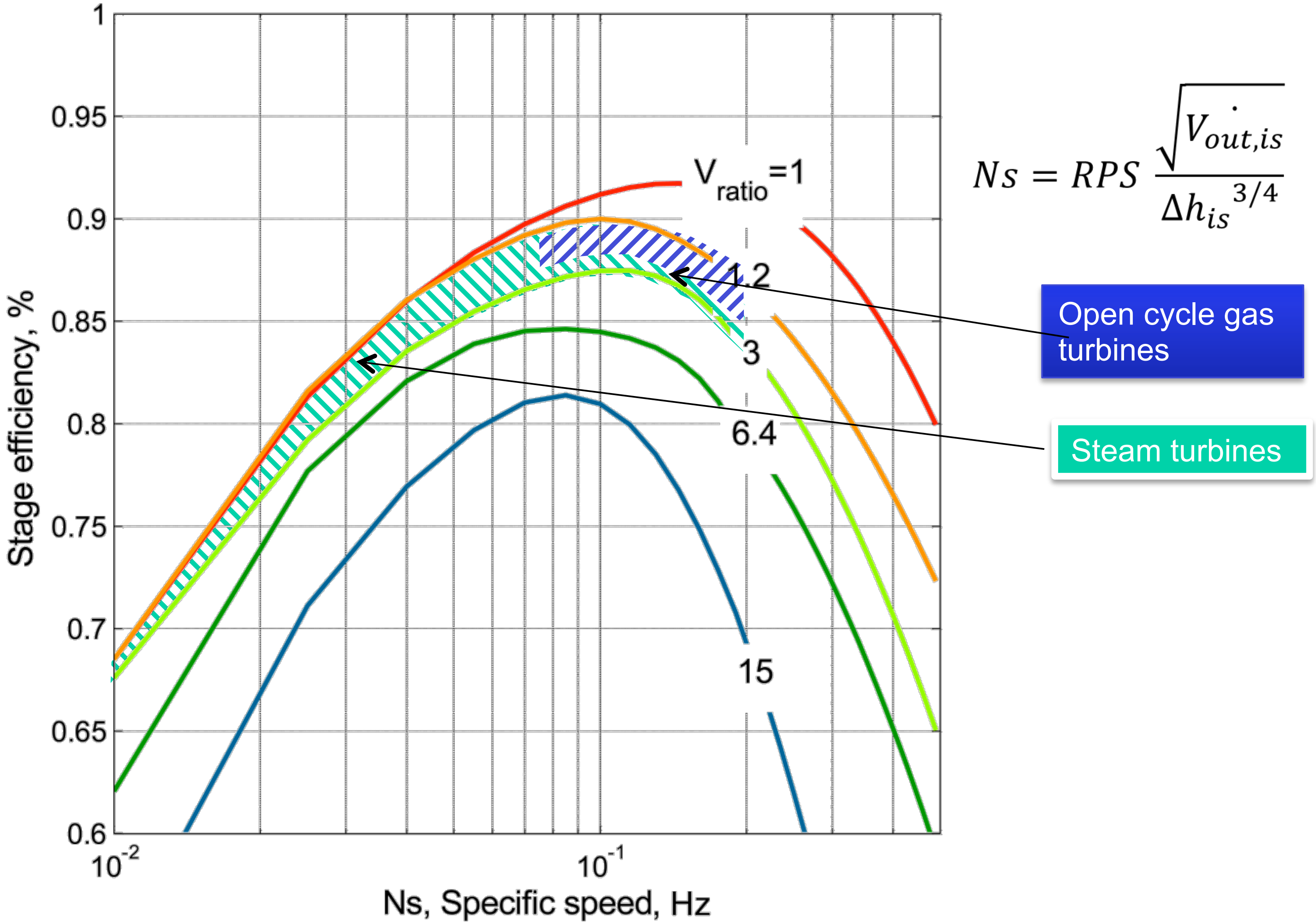
- Other parameters, relevant for the turbine efficiency, are the volume ratio (compressibility effects) and the size parameter (dimensional effects: thickness, clearance, roughness, etc.)

$$V_{ratio} = \frac{\dot{V}_{out,is}}{\dot{V}_{in}} \qquad SP = \frac{\sqrt{\dot{V}_{out,is}}}{\Delta h_{is}^{\;1/4}}$$

Turbine Design

- Both open-cycle gas turbines and steam turbines are characterized by large enthalpy drops (air and steam have light molecules):
  - multi-stage turbines are required
  - the expansion ratio/stage is relatively small
- In open-cycle heavy-duty gas turbines the volumetric flow rate experiences moderate variations along the expansion, so nearly optimum Ns can be adopted in all stages
- In steam cycles, the variation of volumetric flow rate is dramatic: single-shaft solutions must deal with non-optimum Ns (too low in HP, too high in LP)
- ORC turbines are characterized by heavy molecules, small enthalpy drops.

Important parameters in turbine design: specific speed



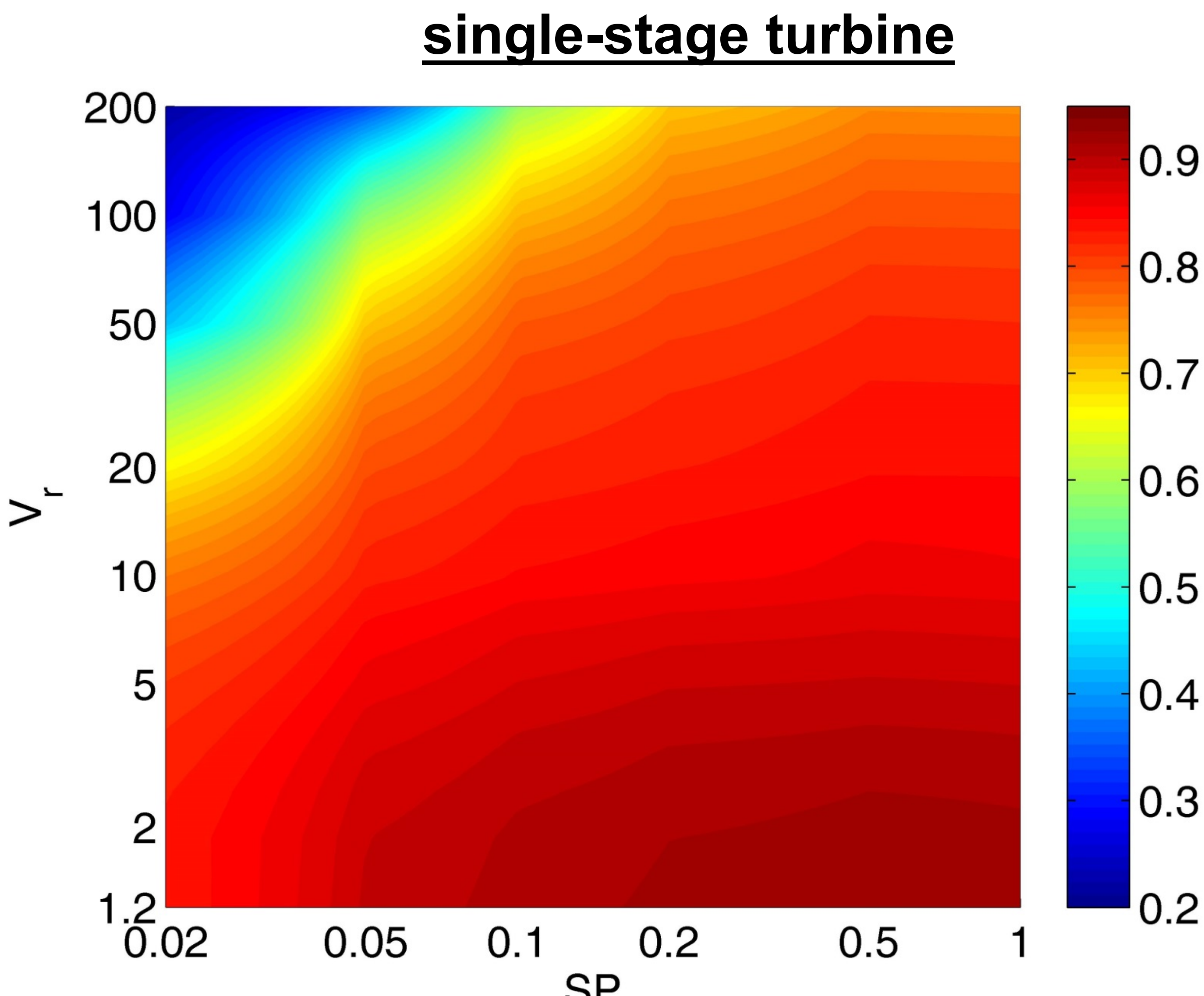
$$Ns = RPS\,\frac{\sqrt{\dot{V}_{out,is}}}{\Delta h_{is}^{3/4}}$$

Turbine Design

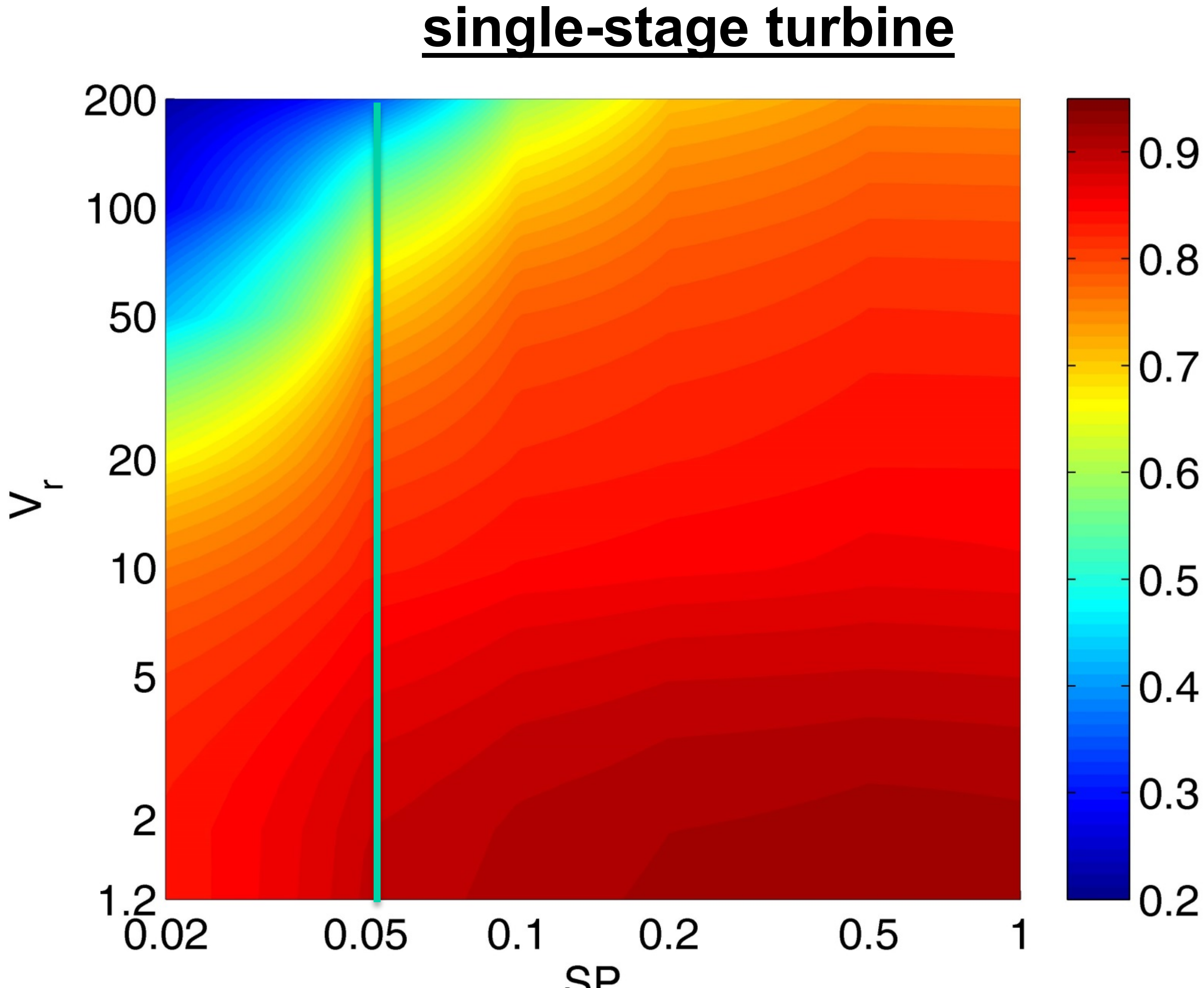
ORC turbines are characterized by:

- heavy molecules → small enthalpy drops → few stages → large Vr per stage relevant compressibility effects (supersonic flows)
- large overall Vr → large blade height variation in multi-stage turbines
- The possibility of:
  - designing the turbine at optimum values of Ns and Ds
  - obtaining a proper SP by selecting the working fluid properties (most relevant one : condensing pressure)

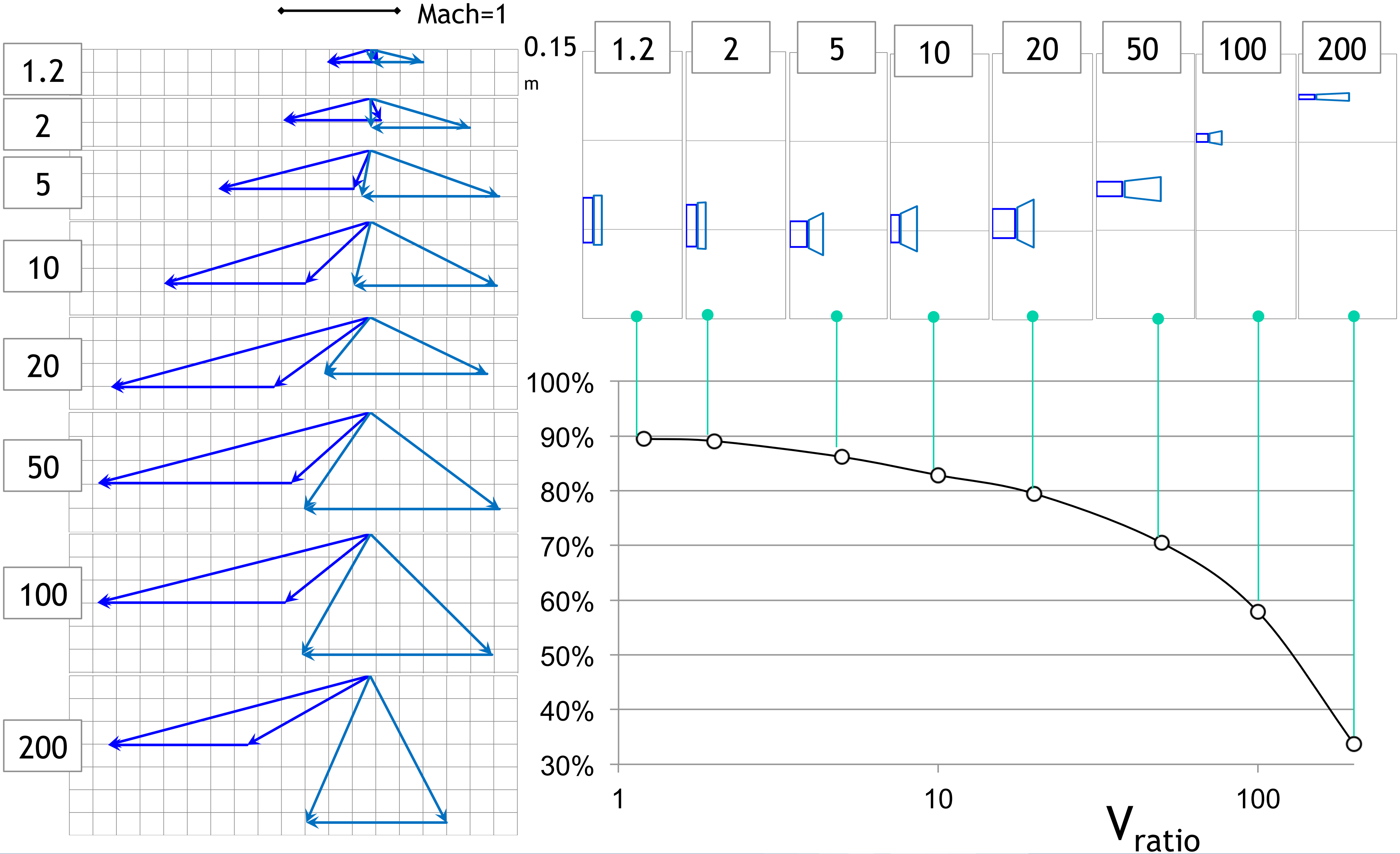
A new efficiency prediction map based on both Vr and SP, for optimized Ns, Ds



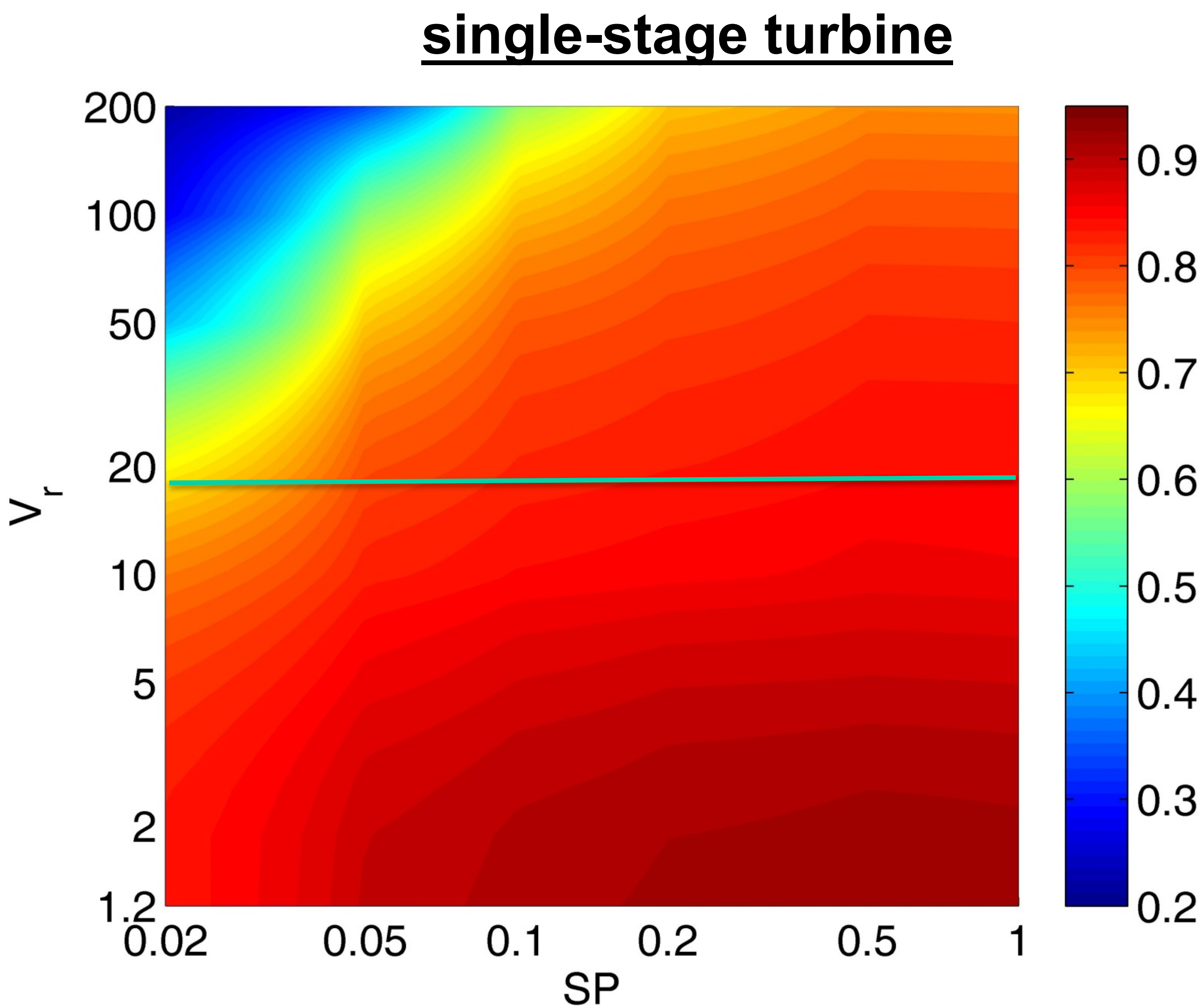
The influence of Vr



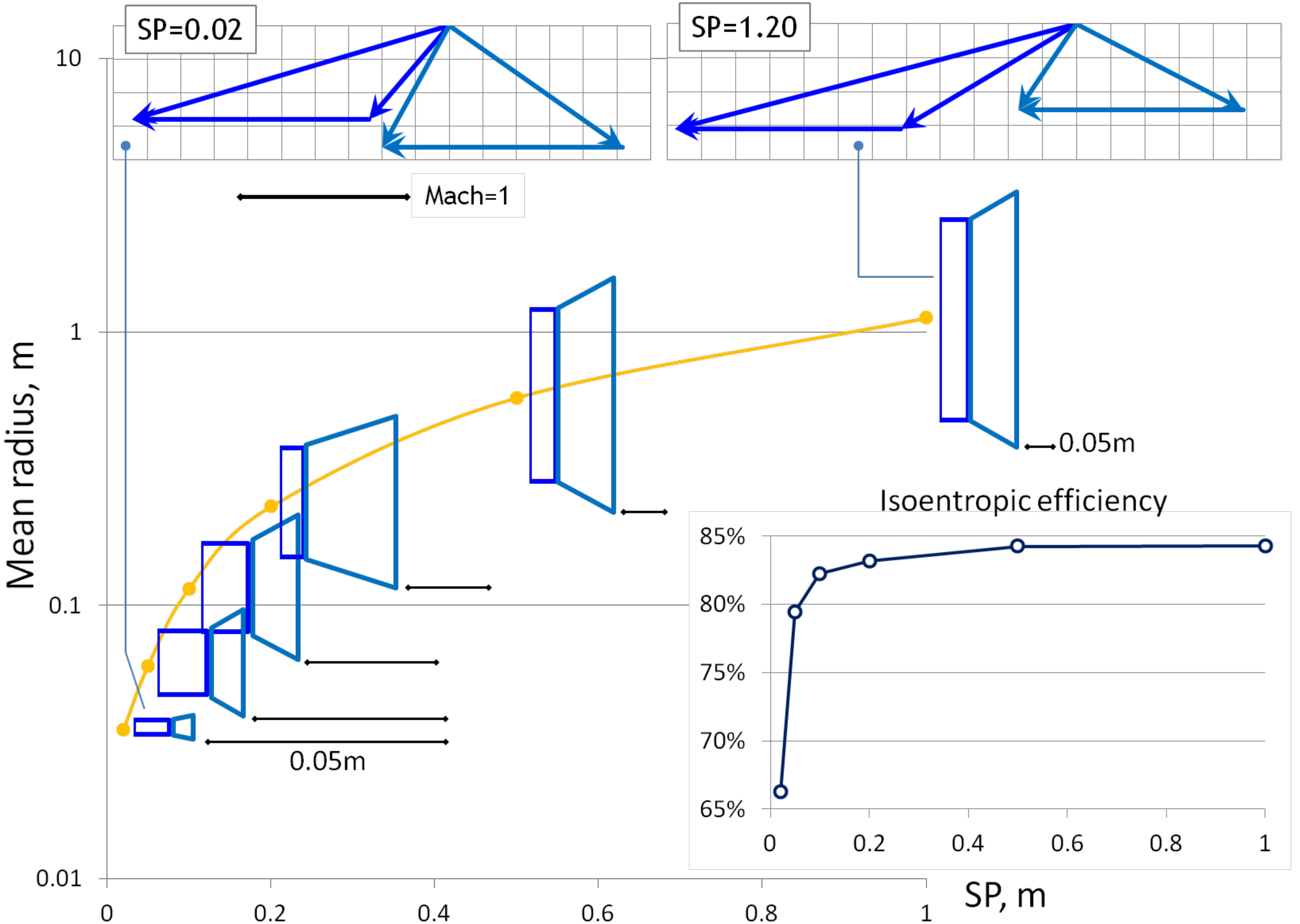
The influence of Vr



The influence of SP

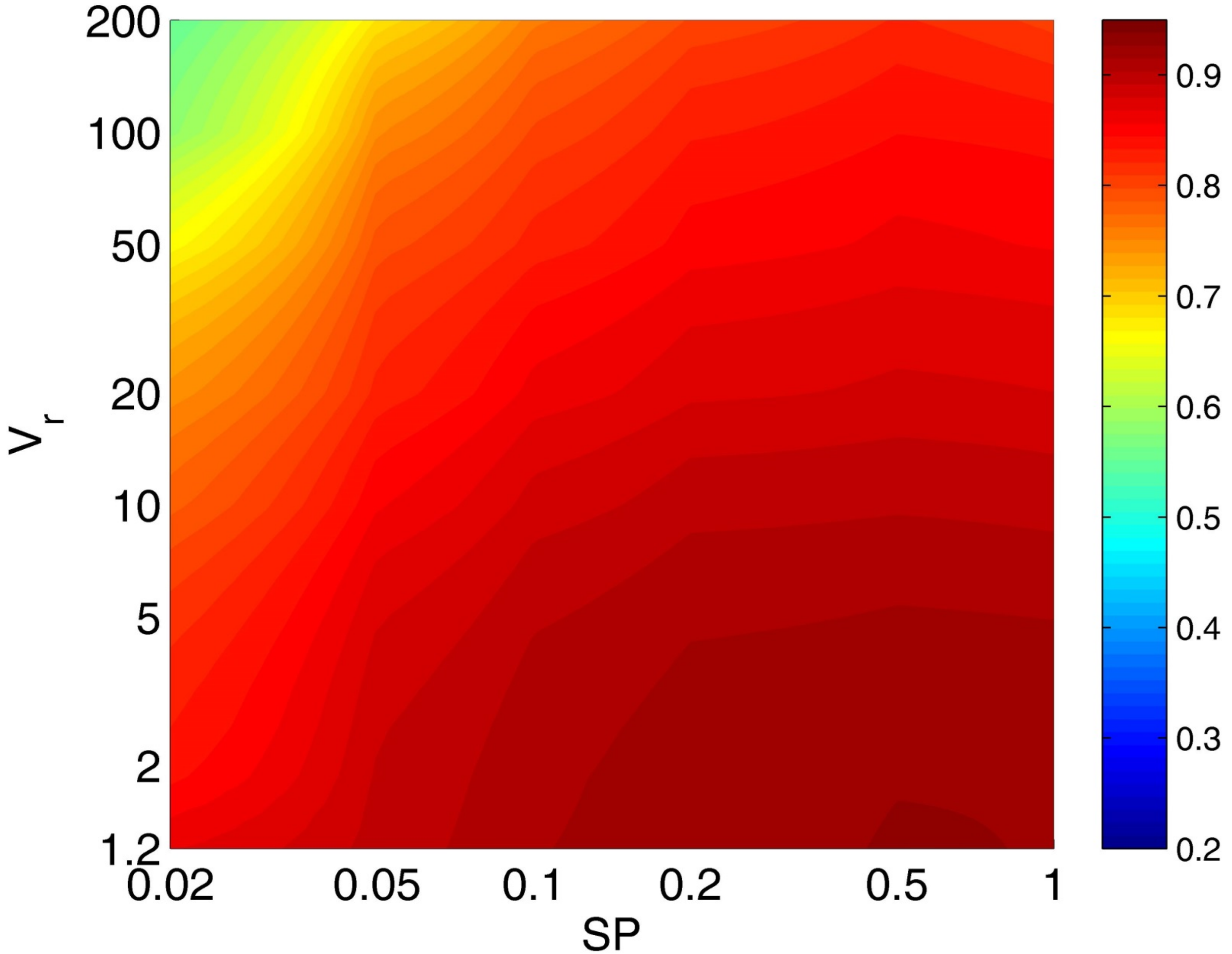


The influence of SP

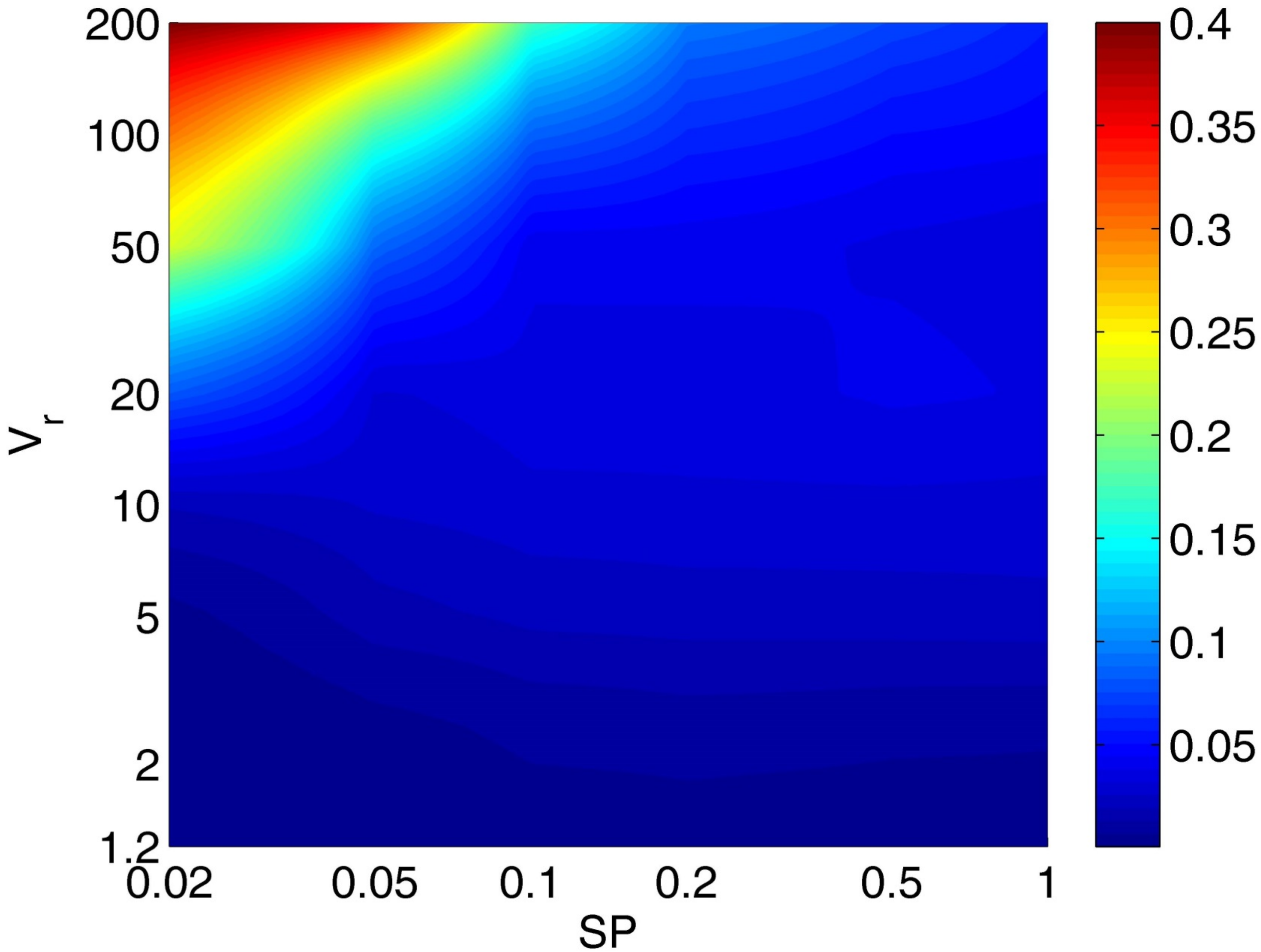


A new efficiency prediction map based on both Vr and SP, for optimized Ns, Ds

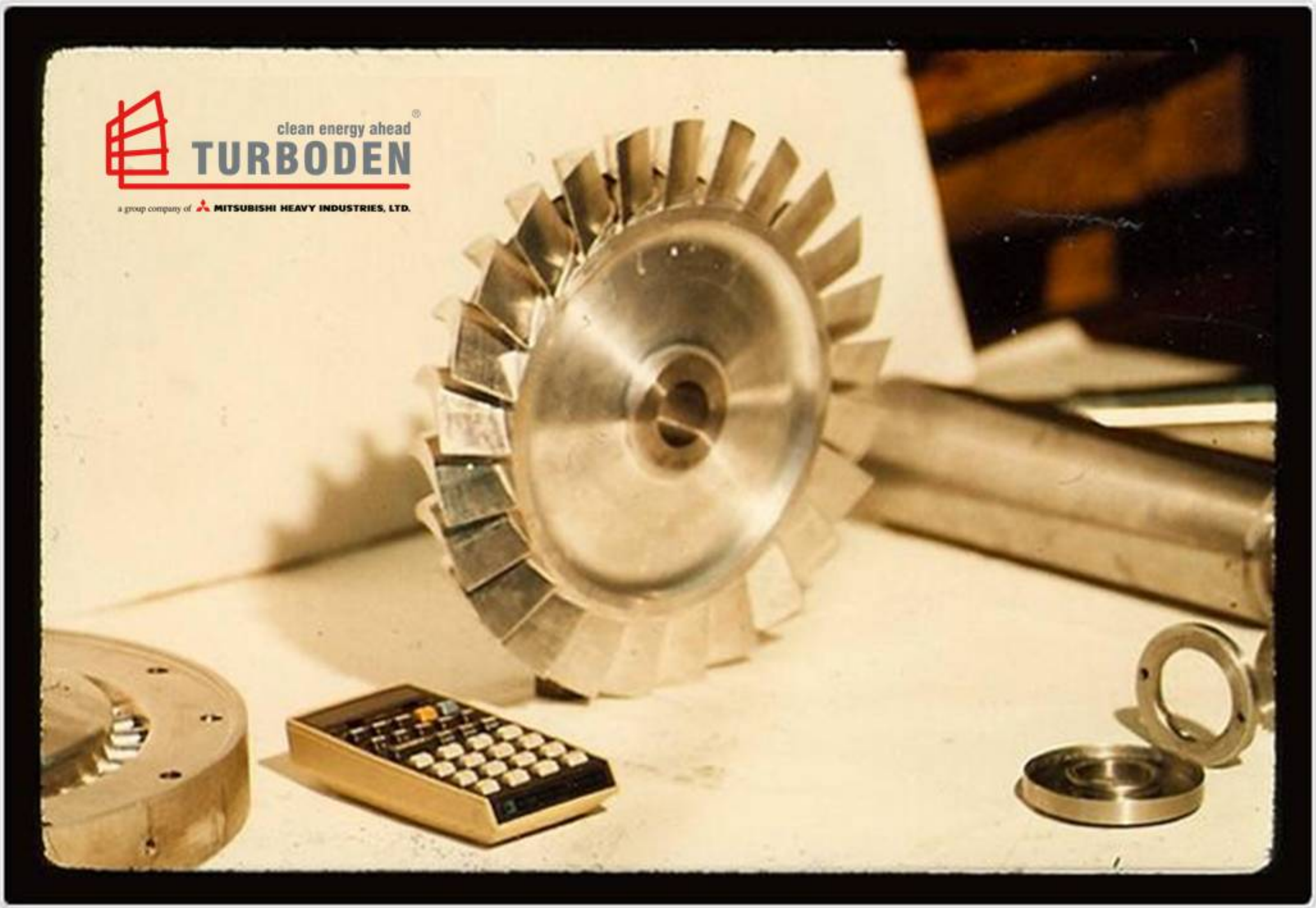
Two-stage turbine



Turbine efficiency improvement achievable by substituting a single stage with a two stages turbine



First example (1978?): single-stage, 3000 rpm, 4 kWel



First example (1978?): single-stage, 3000 rpm, 3-4 kW_{el}

Heat source: hot water (90-70°C)
Heat sink: cold water (15-25 °C)

Working fluid: C_2Cl_4 (perchloroethylene), saturated cycle

- T_{cr} = 121 °C
- M = 166 kg/kmole

The first ORC built by Turboden

Demonstration that it is possible to design a high efficiency (>85%), low mechanical stress turbine, directly coupled to a 3000 rpm generator, even at very low power output

Second example (1979): four stages axial flow turbine, 35 kWel

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Heat source: Thermal oil (380-300°C) from CSP (parabolic through)

Heat sink: water (25-32°C)

Working fluid: Flutec PP3 (C_8F_{16}) recuperated cycle

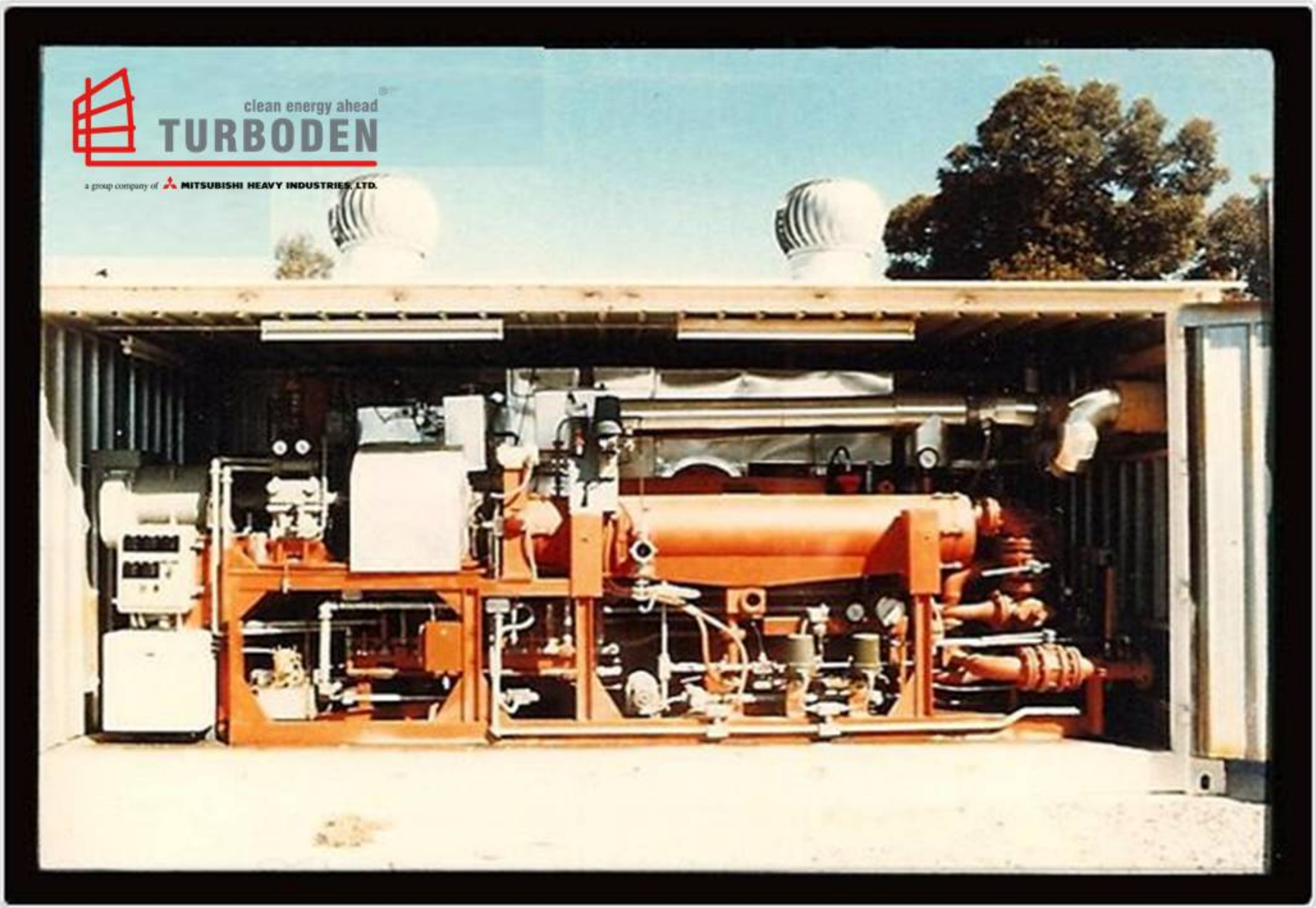
- Tcr = 515 °C
- M = 400 kg/kmole

4 stages:

- first stage impulse, partial ammission
- second stage shrouded (low blade height)
- third and fourth stages reaction stages, untwisted blades

Demonstration that it is possible to design a high efficiency (>85%), low mechanical stress turbine, directly coupled to a 3000 rpm generator, even for very high expansion ratio

Bado G., Tomei G., Angelino G., Gaia M., Macchi E. "THE ANSAL-DO 35 kW SOLAR POWER SYSTEM", Proceedings of International Solar Energy Society (ISES) Congress, Atlanta (USA), in "SUN II" Vol. 2, pp. 1090-1094, Pergamon Press, May 1979.



Third example (2012): single-stage axial-flow turbine, R-134a 500 kWel (see ENEL presentation, this congress)

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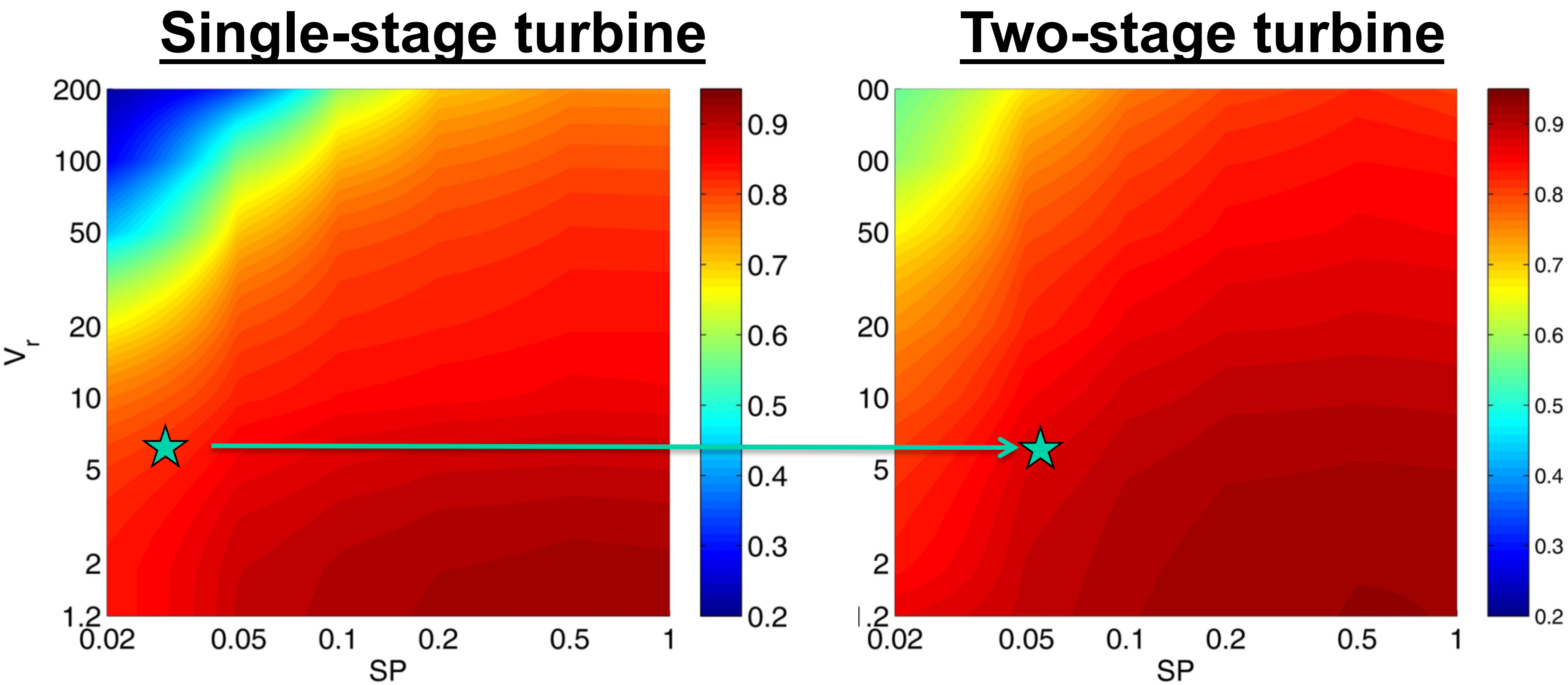
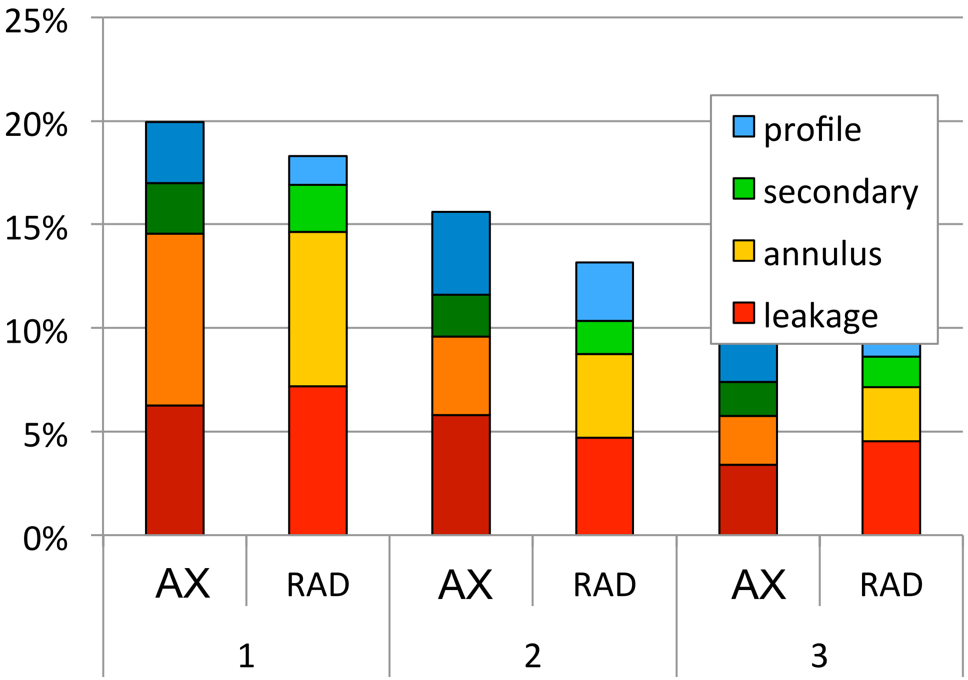
- The test turbine was a single-stage, low Ns, SP axial turbine (500 kW)
- The scaled-up turbine will be a two-stage, high efficiency axial turbine (10 MW)



Fourth example: 1000 kWel, 3 stages out-flow, working fluid: Flutec PP1, hot source: hot water (170 °C) cold sink: ambient air

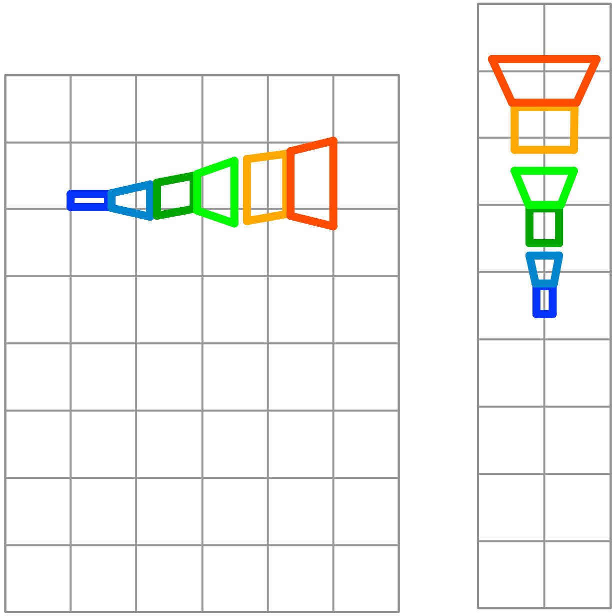
RADIAL OUTFLOW vs AXIAL TURBINE

Losses breakdown



Δh	AX	RAD
1	31.9%	24.9%
2	31.9%	32.5%
3	36.2%	42.7%

η	AX	RAD
1	79.3%	81.3%
2	84.1%	86.4%
3	85.5%	89.1%



Radial vs Axial

Efficiency
+ 4.14%

For the same ORC

Fourth example: 1000 kWel, 3 stages out-flow, working fluid: Flutec PP1, hot source: hot water (170 °C) cold sink: ambient air

Fifth example: 1 MWel, 4 stages outflow, working fluid: hydrocarbon


EXERGY

THANK YOU FOR YOUR ATTENTION !