1st International Seminar on ORC Power Systems

Sept 22-23, 2011 – Delft, NL

Design, Simulation and Construction of a Test Rig for Organic Vapours

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POLITECNICO DI MILANO

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in collaboration with

TURBODEN
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Motivation

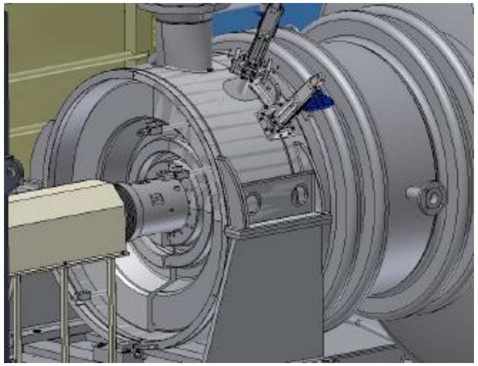
Increase ORC turbine efficiencies via passage flow field investigation

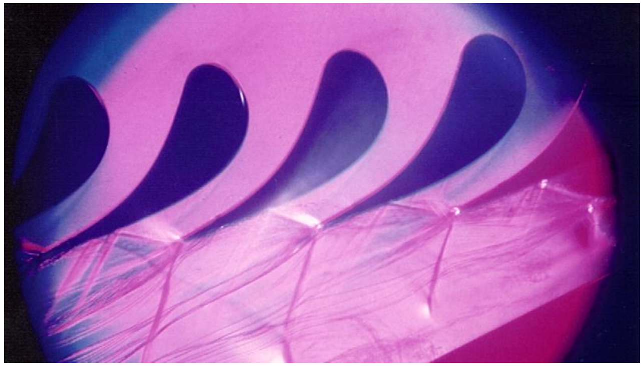
→ **Experimental investigation of ORC turbine passage flows**

NO experimental data for flows within ORC turbine blade passages

- **Properties** T_T, P_T, P, u, α, ψ
- **Independent** measurement of P and $\boldsymbol{u}$ field — **direct measurement of $\boldsymbol{u}$**
  consistency of thermodynamic models — e.g. $h(P_T, T_T) = h(P, T) + |\boldsymbol{u}|^2/2$
- **Techniques** total pressure probes & pressure taps (P_T, P)
  thermocouples (T_T), LDV (v), Schlieren *(shock waves)*

limited investigation in **industrial plants** → **TROVA** (*Test Rig for Organic Vapors*)





Summary

→ Background on ORC

→ Design of the TROVA

→ Dynamic simulation of the TROVA

→ Construction of the TROVA

→ Conclusions

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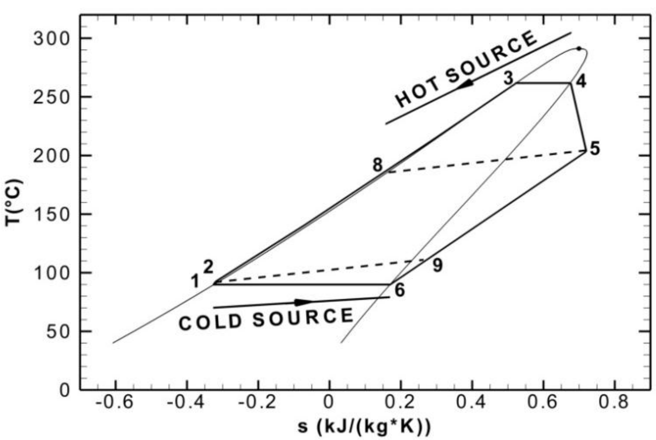
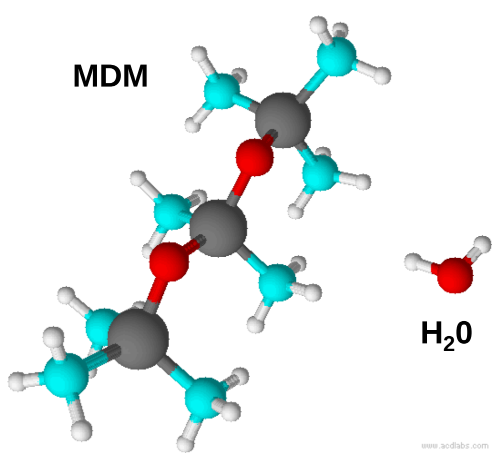
Rankine cycle + organic working fluid – **Mm , complexity**

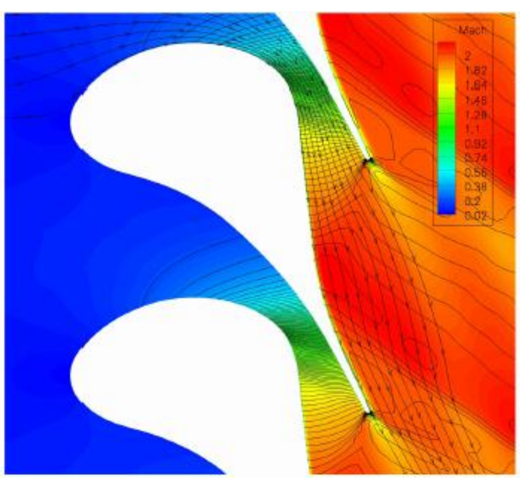
- Advantages on cycle, plant, operation → viable technology, low/med T, W_{el}
- Disadvantages on turbine flows – real-gas effects, low speed of sound – limited knowledge of expansions (η_T – design tools)

State of the art

novel real-gas models (*Span-Wagner*) + CFD (*zFlow*) , separate validations







Background – ORC & turbine flow

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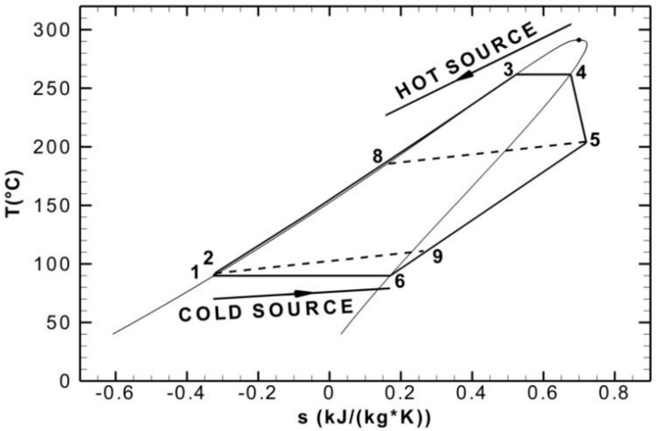
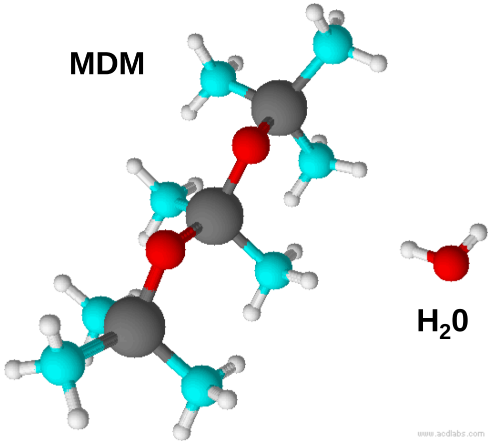
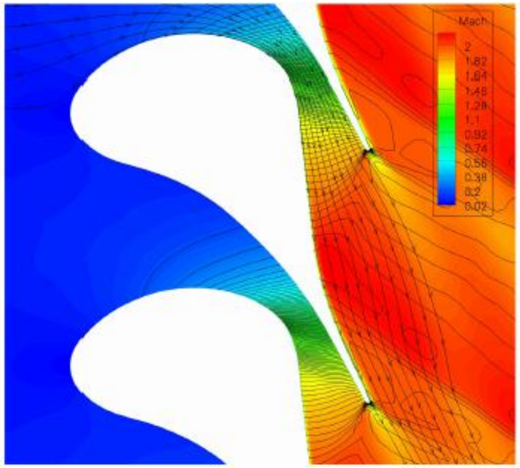
→ **PROVIDE EXPERIMENTAL DATA ON FLOWS TYPICAL OF ORC TURBINE PASSAGE**







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→ Conclusions

Dedicated facility – Design

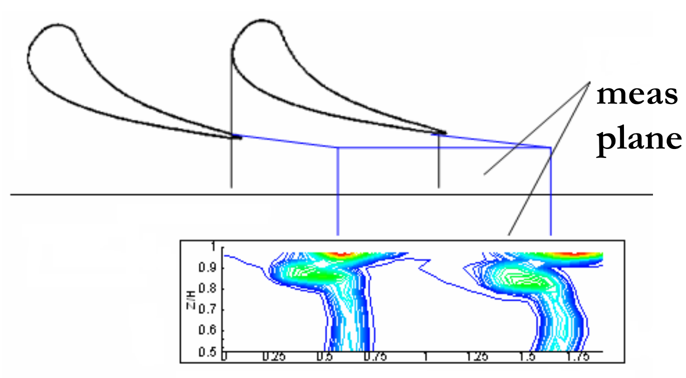
- Limits for investigation industrial ORC plants
- Controlled flow for calibration

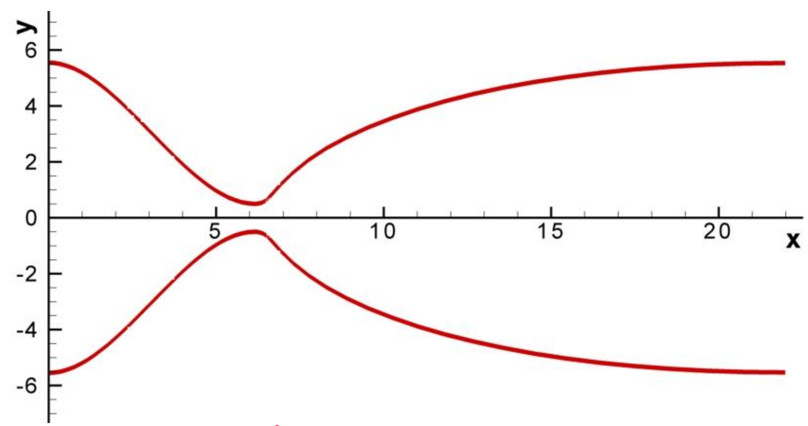
TEST SECTION: planar **straight axis** convergent – divergent **nozzle**
quasi – 1D, isentropic expansion (no calibrated probes)

FLUIDS: Siloxanes & Hydrofluorocarbons – thermodynamics, safety
Siloxane **MDM** (high T) & HFC **R245fa** (low T)

OP COND: parameters A_t – $P_{T,6}$, T_{T6} – β_{max} – P_7

CYCLE: Gas cycle vs Phase transition cycle
high **costs** for continuous operation





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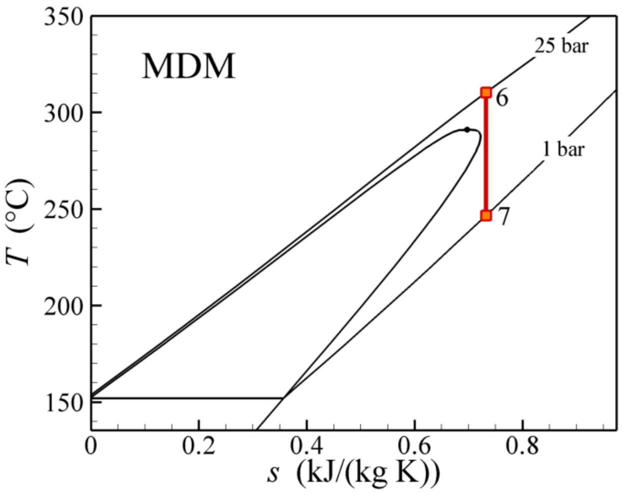
	P_{T6} (bar)	T_{T6} (°C)	β	A_t (mm²)	c_t (m/s)	M_t	m (kg/s)
MDM	25	310	25	314	63.6	1	6.25
R245f	37	159.2	18.5	314	104.3	1	5.4

a

$$M_t = \frac{\sqrt{2\left[h_{T,6} - h(\rho_t, s_6)\right]}}{c(\rho_t, s_6)}$$

$$m = \rho_t A_t c_t$$



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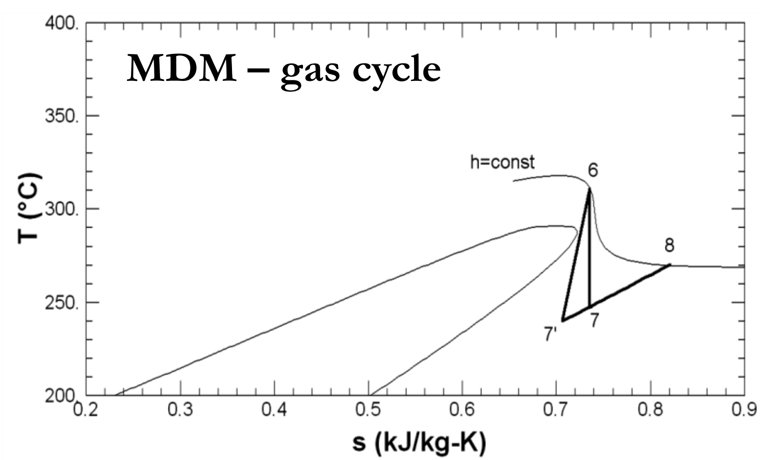

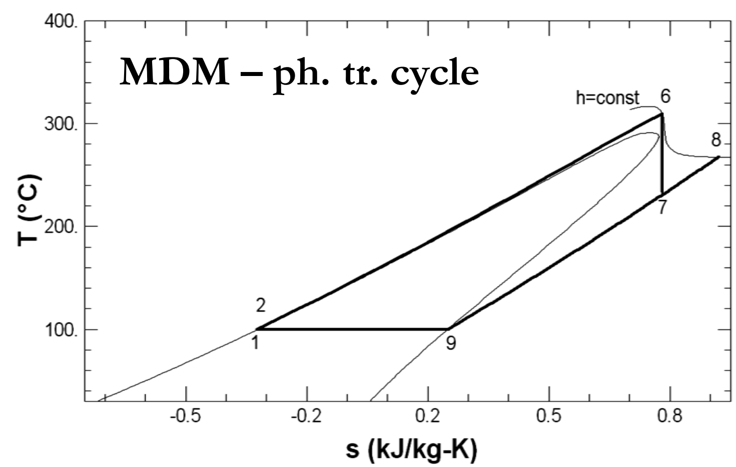

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TROVA – A blow down facility

Closed loop – phase transition – batch operating facility

- ↓ **power –** ↑ **energy** exchange time: storage $P_{T,4} > P_{T,6}$ – limited test duration
- **Unsteady nozzle flow:** constant $P_{T,6}$ (MCV) – change in $h_{T,6}$ (HPV)

  → **sequence of steady flows** with transient operating conditions $P_{T,6}$, $T_{T,6}$

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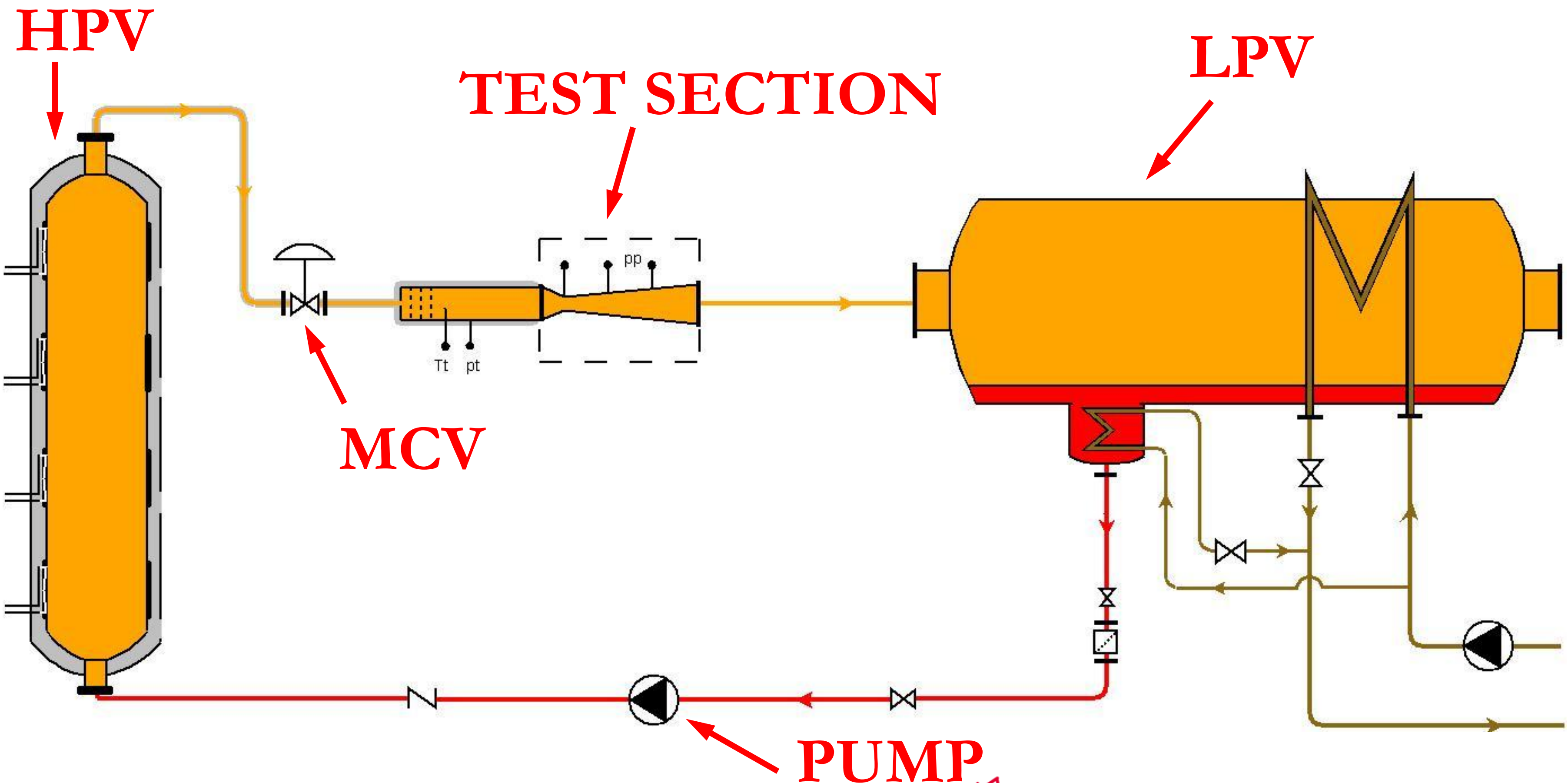

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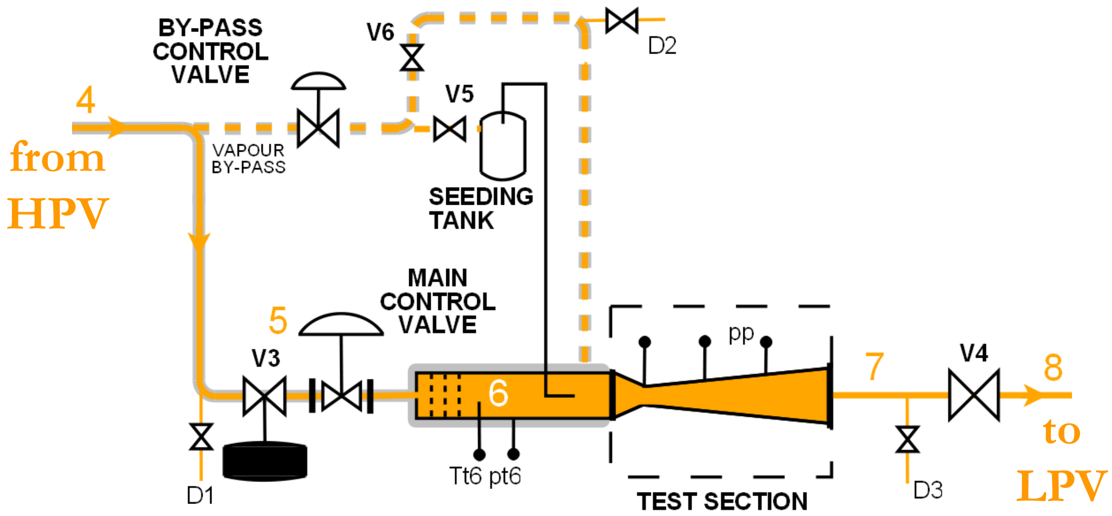
Sizing procedure & results

EVALUATE HPV/LPV V, P, T → $t_{min} \approx 20$ s

Iterative nozzle flow calculation – Lumped parameter – MDM , R245fa

- **Parameters setting** V_{HPV} , V_{LPV} , P_{HPV}
- **Initial conditions** nozzle flow operating conditions
- **Calculation $t \rightarrow$** unsteady mass & energy bal. – vessels b.c. update
- **Calculation stop** $P_{T,5}=P_{T,6}$ or $\perp$ shock at exit
- **Parameters update** if $t_{ex} \leq t_{min}$
- **Safety check** P_{max} for tanks connection



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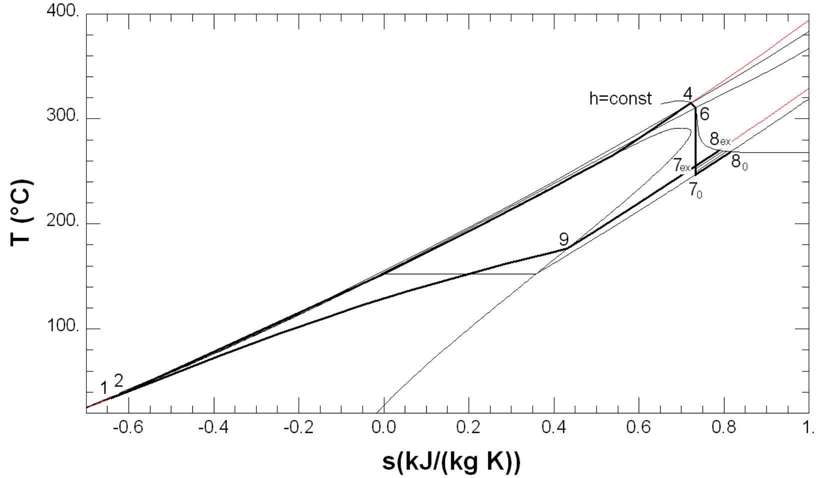
MDM – Vessels design

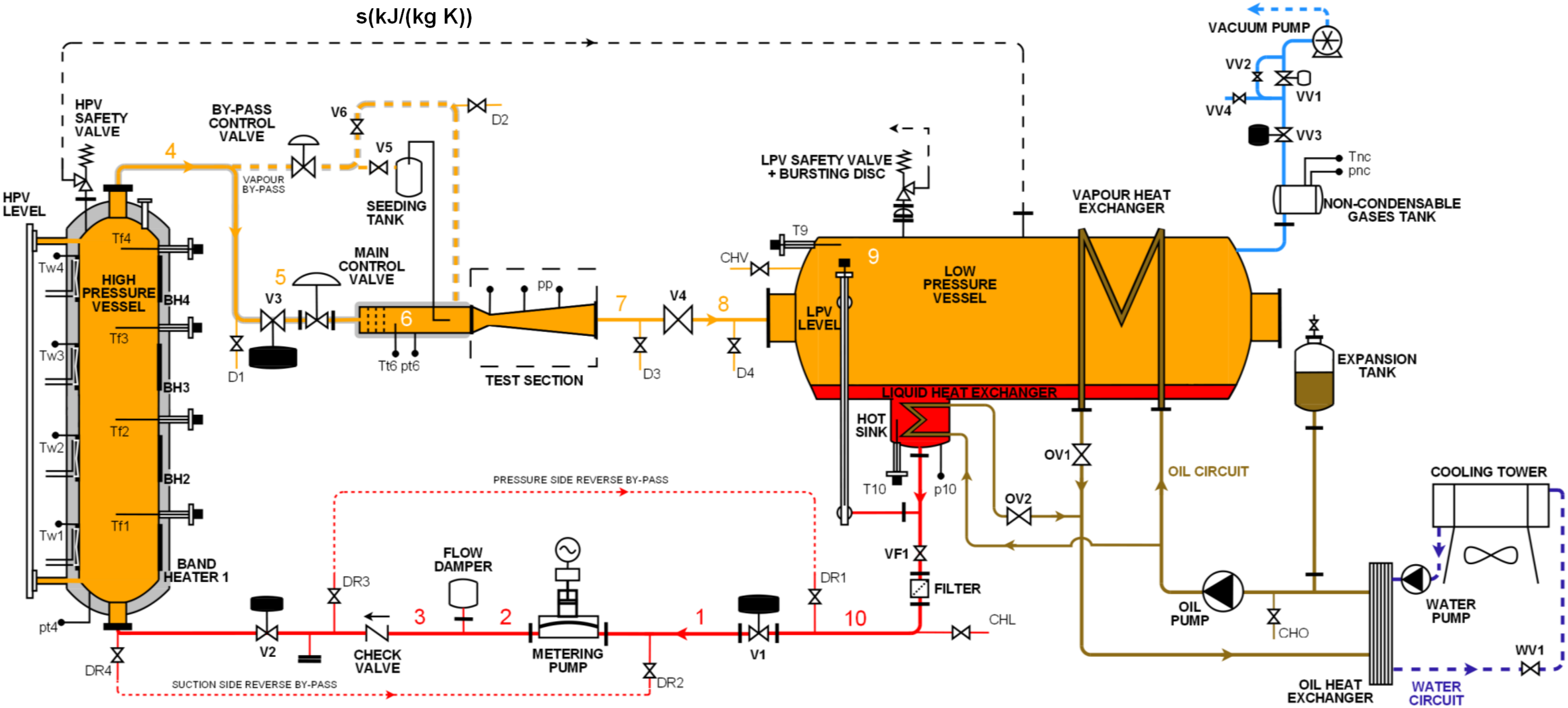
	HPV	LPV
V (m^3)	$\boxed{1.0}$	$\boxed{5.6}$
P_{max} (bar)	$\boxed{50.0}$	$\boxed{20.0}$
T_{max} (°C)	400.0	400.0

MDM – HPV conditions, tests

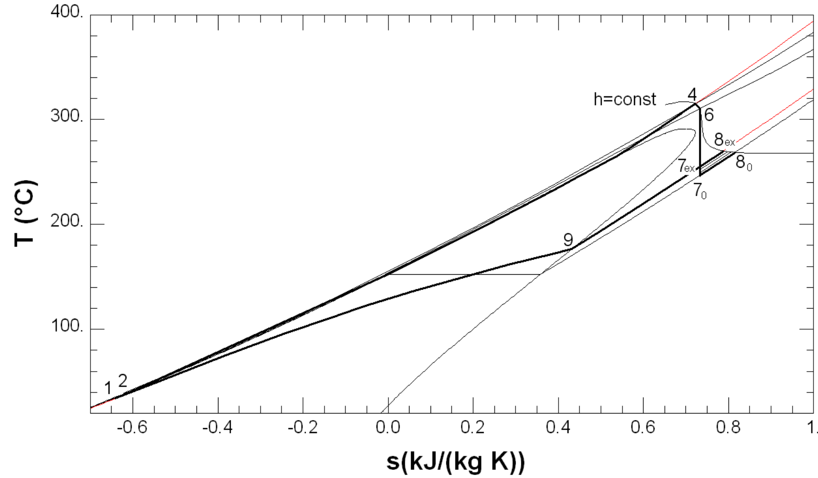
	MDM	R245fa
$P_{T,4(t=0)}$ (bar)	50	50
$T_{T,4(t=0)}$ (°C)	315	176.5
t_{ex} (s)	$\boxed{12}$	$\boxed{28.5}$

Overview

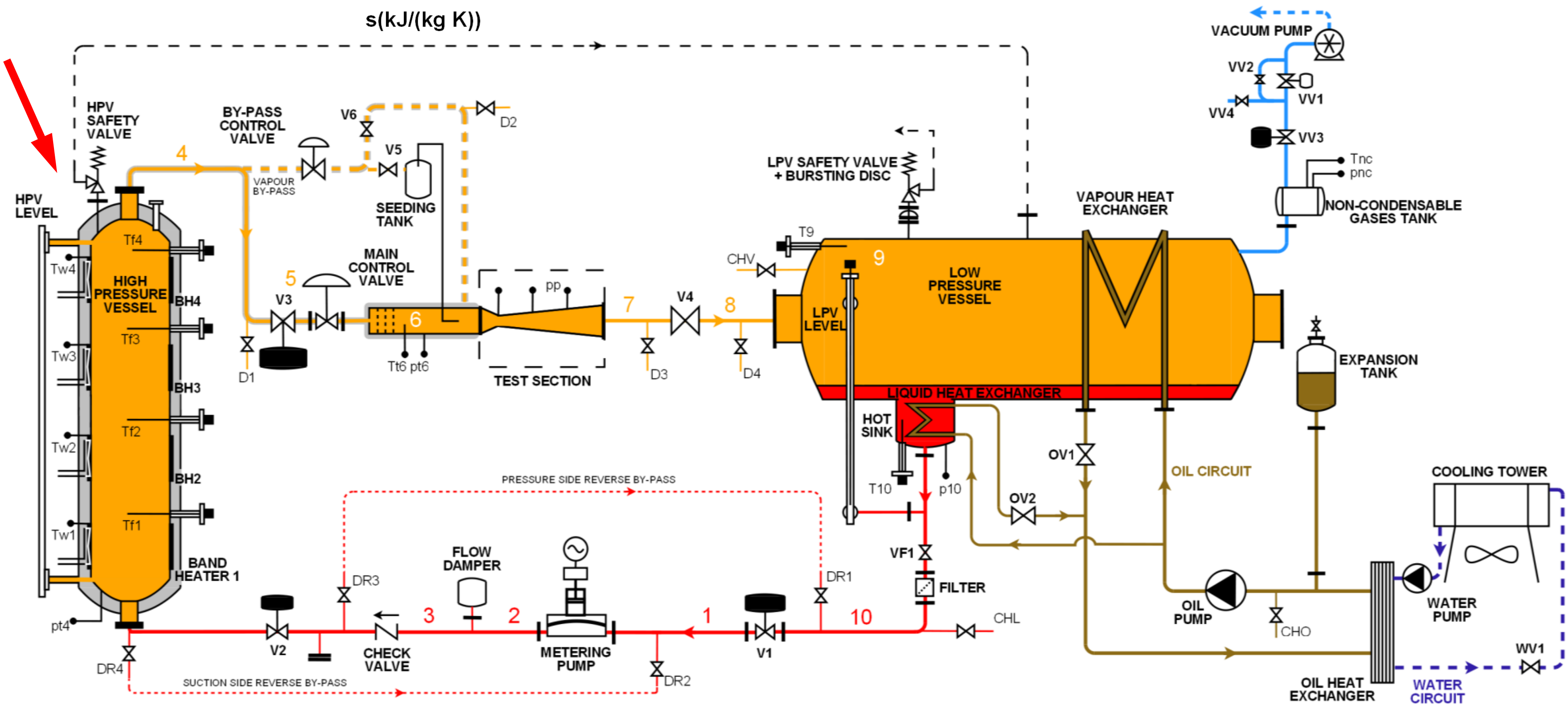

400.
300.
200.
100.
T (°C)
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.
s(kJ/(kg K))
h=const
4
6
8ex
80
7ex
70
9
1
2


VACUUM PUMP
VV2
VV1
VV4
VV3
Tnc
pnc
NON-CONDENSABLE GASES TANK
HPV SAFETY VALVE
BY-PASS CONTROL VALVE
V6
D2
V5
VAPOUR BY-PASS
SEEDING TANK
HPV LEVEL
LPV SAFETY VALVE + BURSTING DISC
VAPOUR HEAT EXCHANGER
T9
CHV
Tf4
Tw4
HIGH PRESSURE VESSEL
BH4
MAIN CONTROL VALVE
V3
pp
TEST SECTION
V4
LOW PRESSURE VESSEL
LPV LEVEL
D1
Tt6 pt6
D3
D4
EXPANSION TANK
Tf3
Tw3
BH3
LIQUID HEAT EXCHANGER
HOT SINK
OV1
OIL CIRCUIT
Tf2
Tw2
BH2
T10
p10
OV2
COOLING TOWER
PRESSURE SIDE REVERSE BY-PASS
Tf1
Tw1
BAND HEATER 1
FLOW DAMPER
VF1
FILTER
DR3
DR1
OIL PUMP
WATER PUMP
pt4
V2
CHECK VALVE
METERING PUMP
V1
CHL
CHO
WV1
DR4
SUCTION SIDE REVERSE BY-PASS
DR2
OIL HEAT EXCHANGER
WATER CIRCUIT

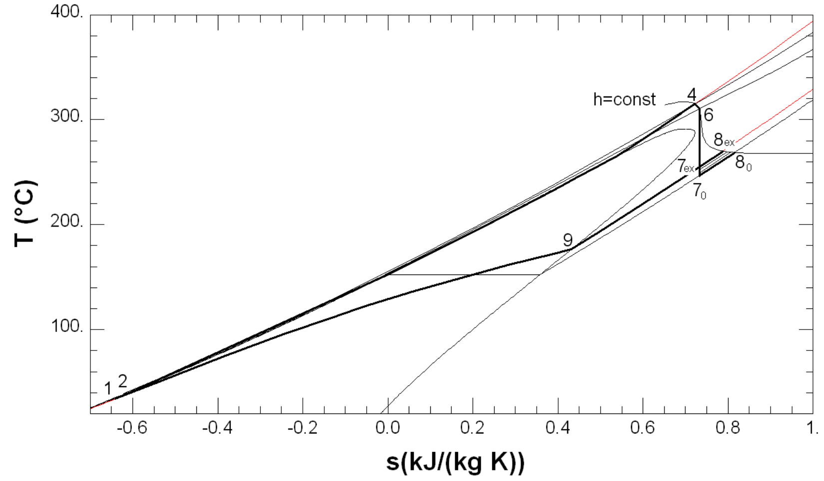
Overview



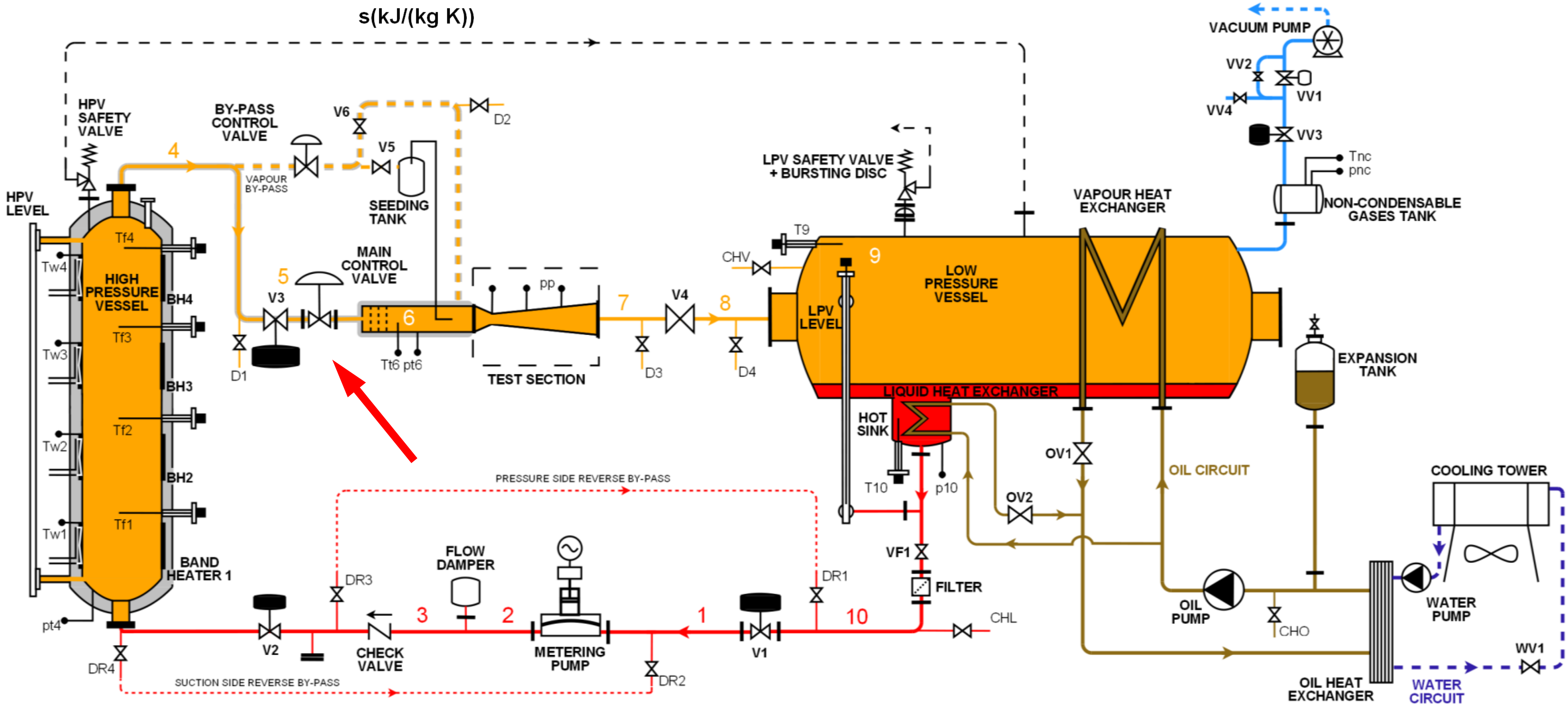
HEATING SECTION



Overview



THROTTLING SECTION



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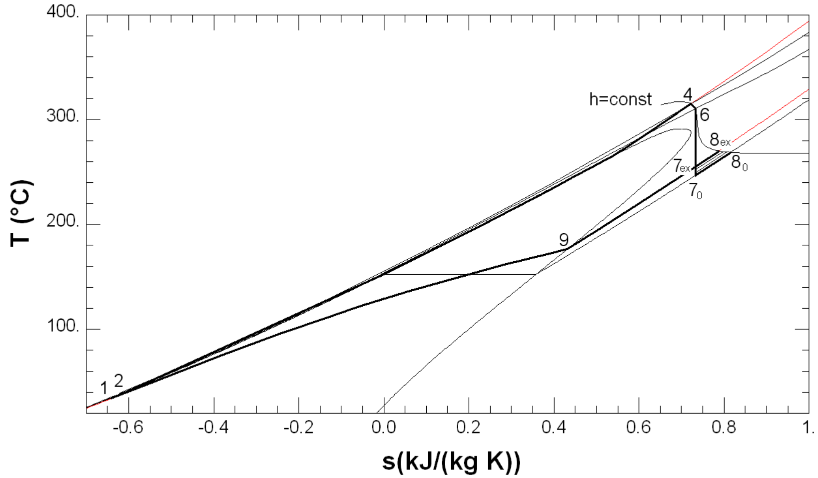
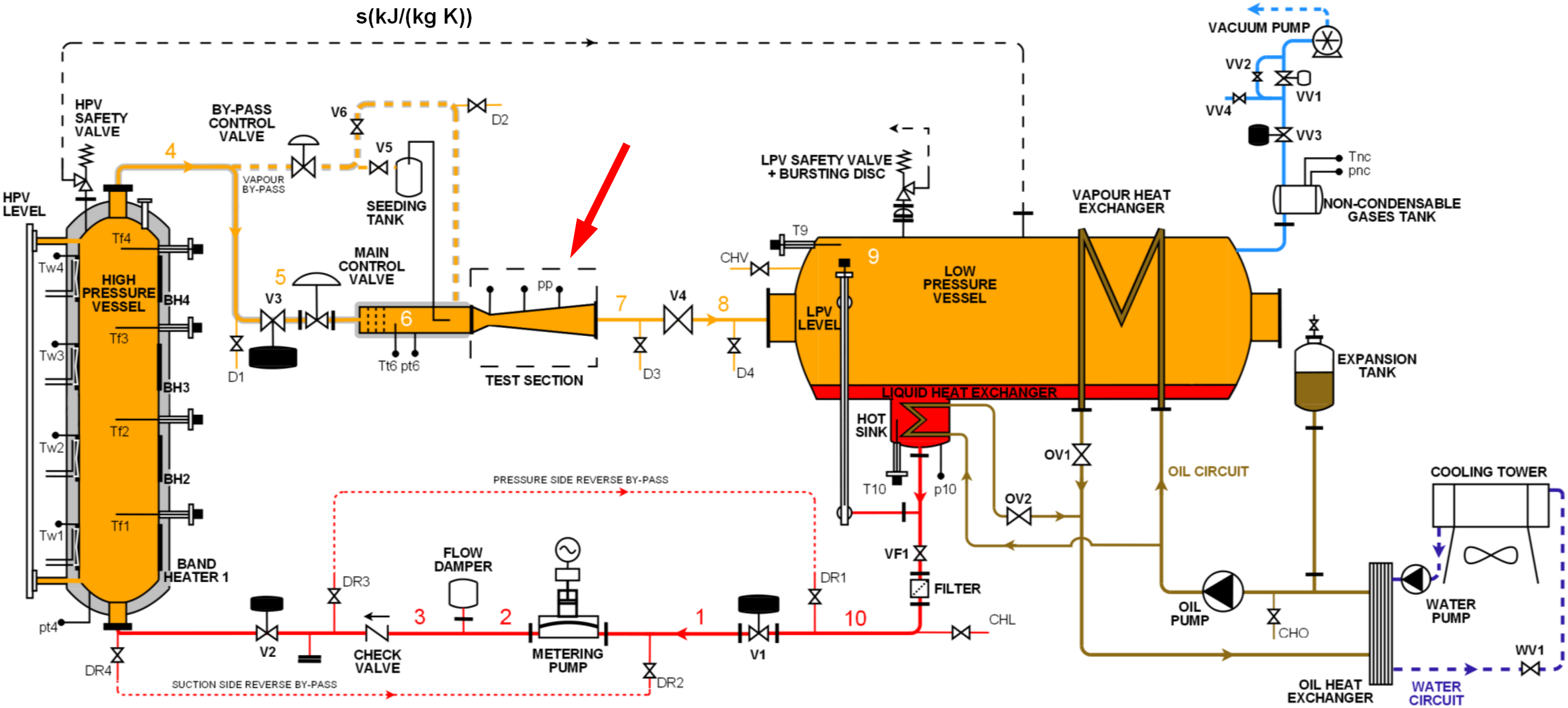
Overview



TEST SECTION



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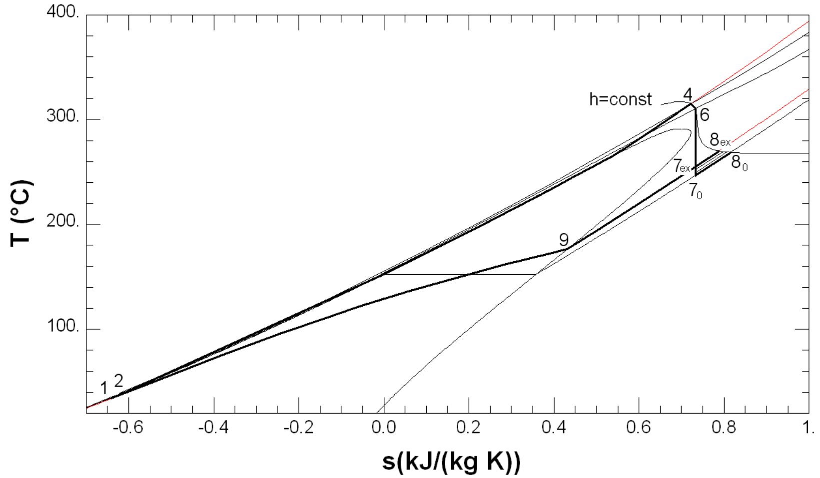
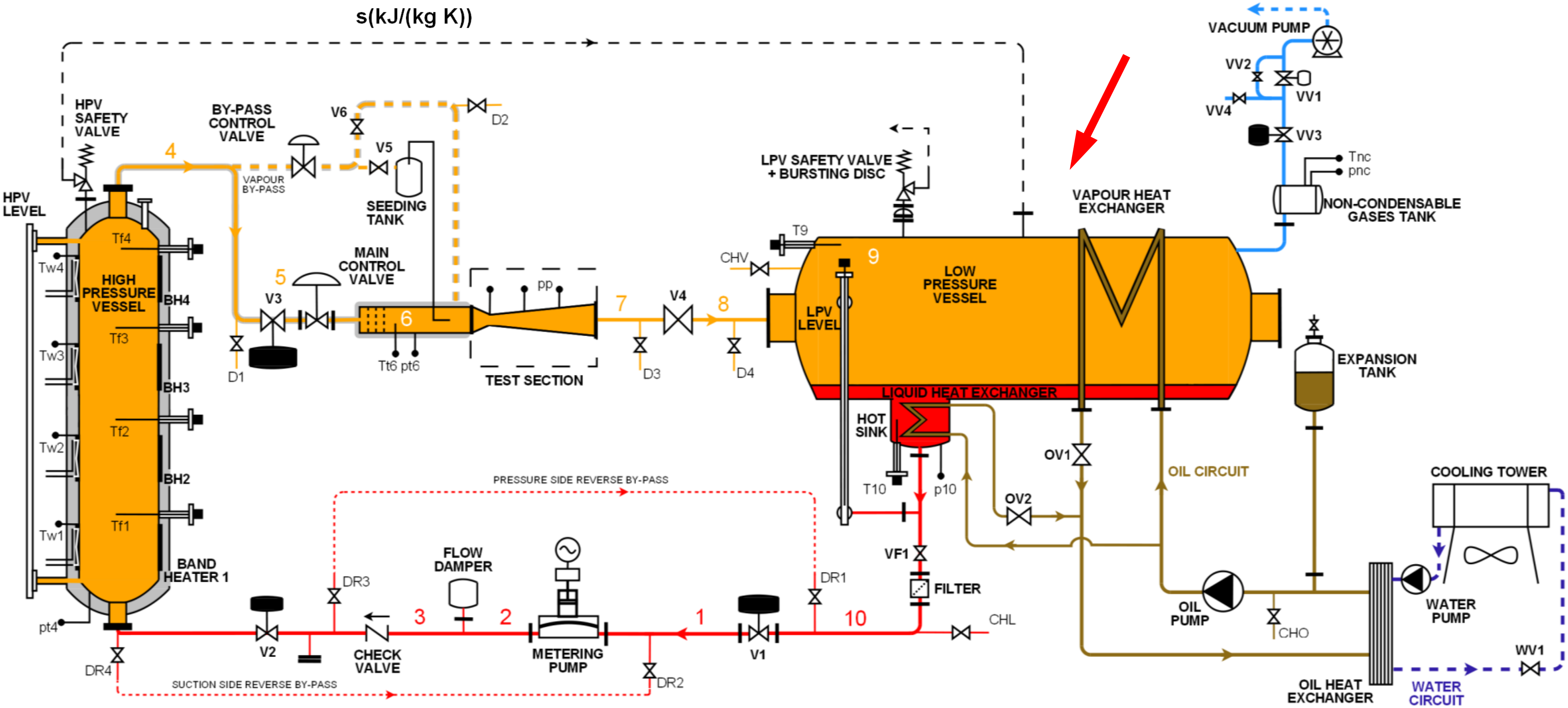


COOLING SECTION



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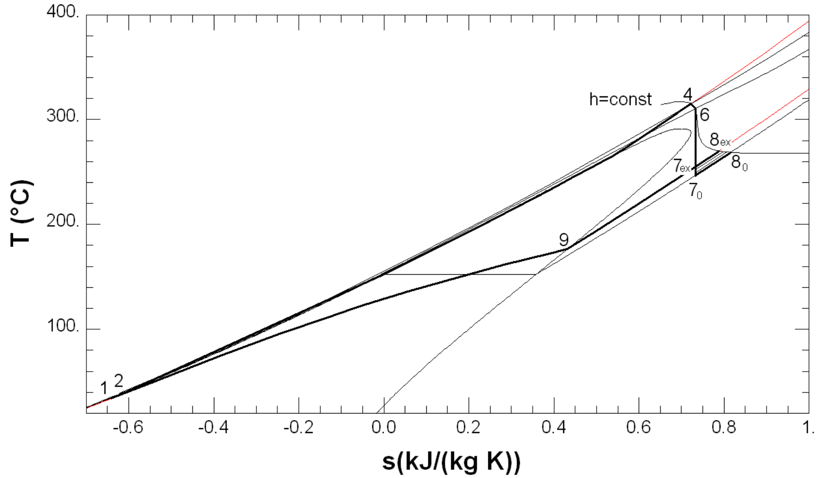
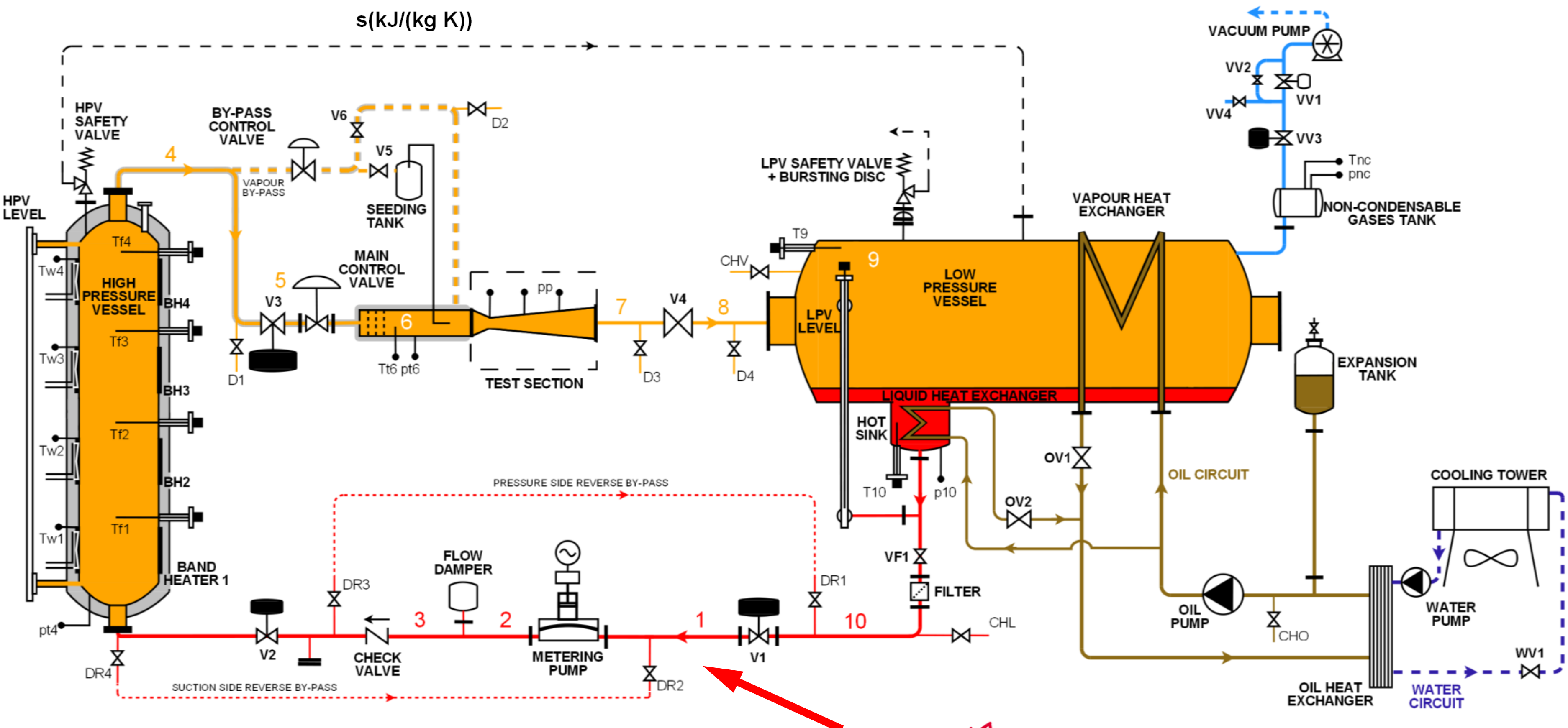


COMPRESSION SECTION



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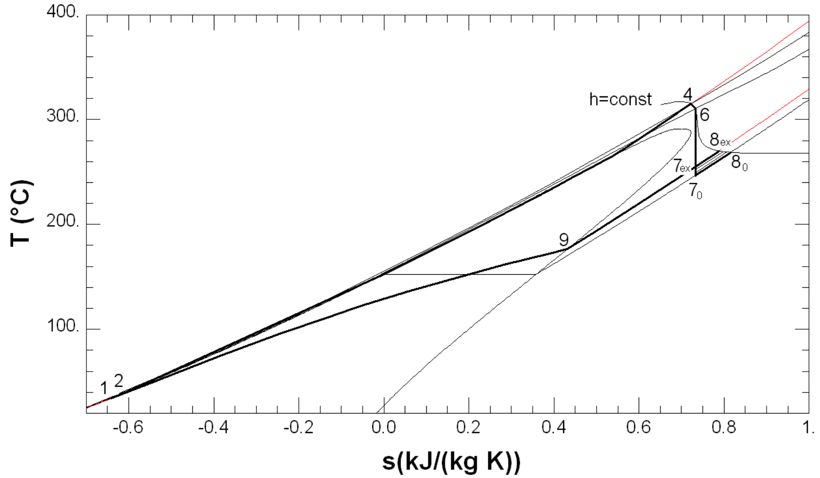
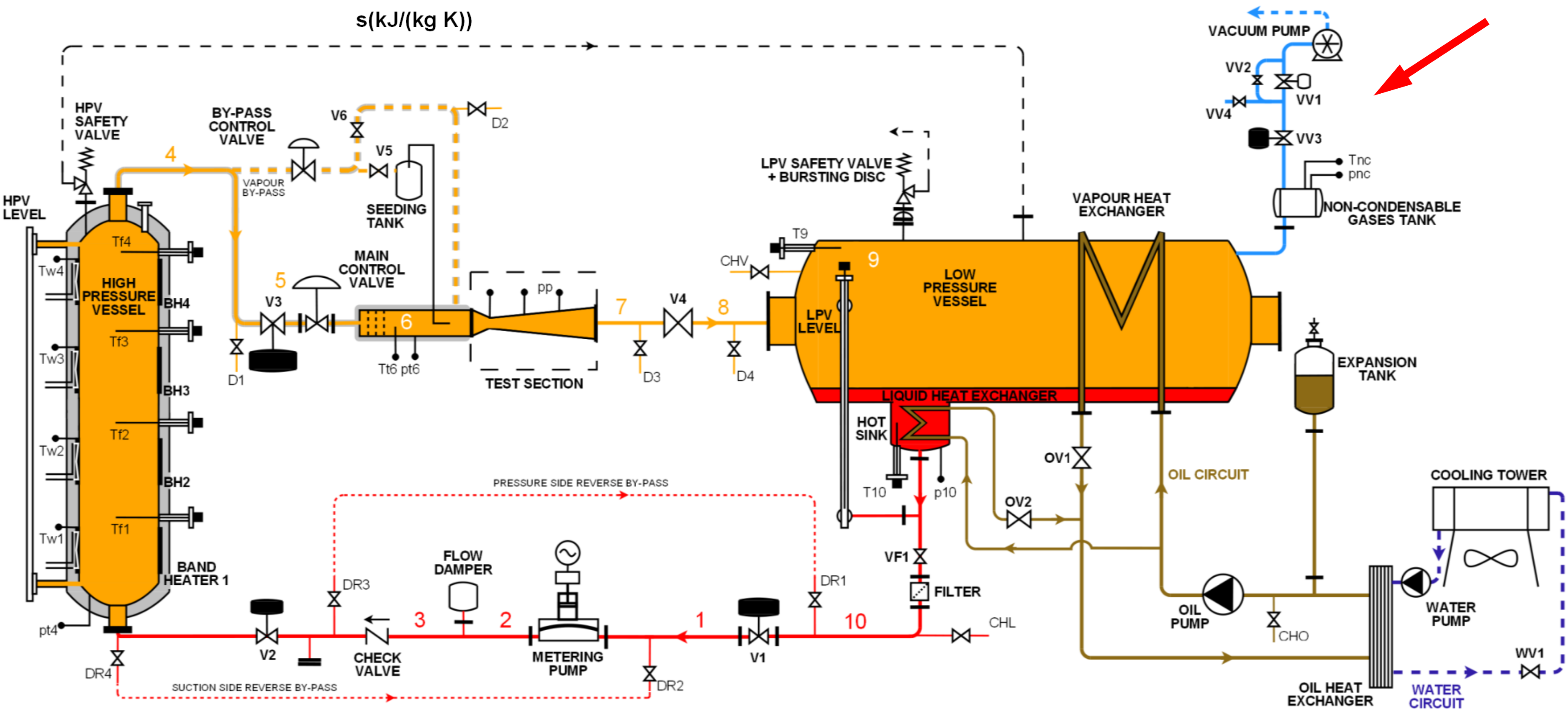


VACUUM SECTION



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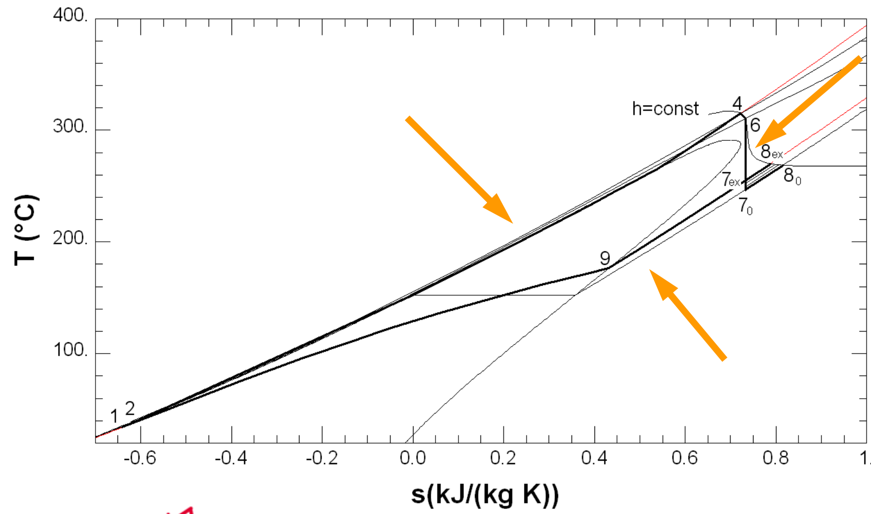
Dynamic simulation

Batch operation + **control** systems → **START-UP** and **TEST** time

- **Processes to simulate:** heating – test – condensation
- **Batch simulation:** batch operation of the facility
- **Model approaches:** lumped parameter / 1D (plant) + 1D (nozzle)
- **Simulation tools:** *Modelica* (object-oriented language) + *FluidProp*
  simple models → complex model
  Fortran + *FluidProp*
- **Self-made library:** lack of component models – e.g. nozzle → *TestRig*



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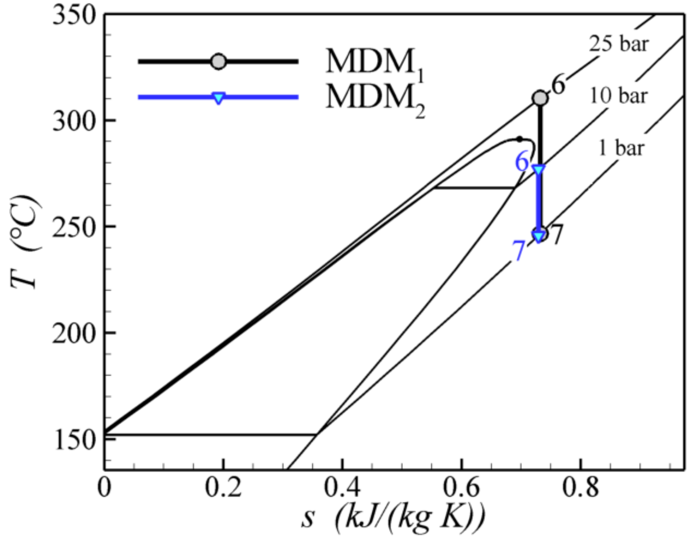
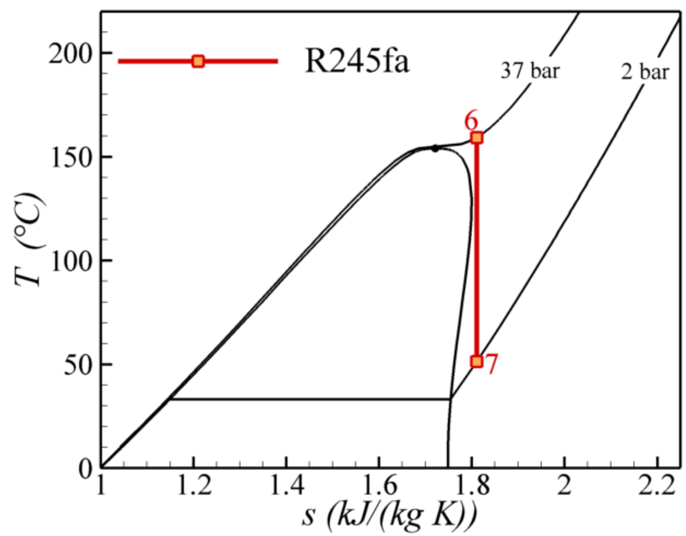
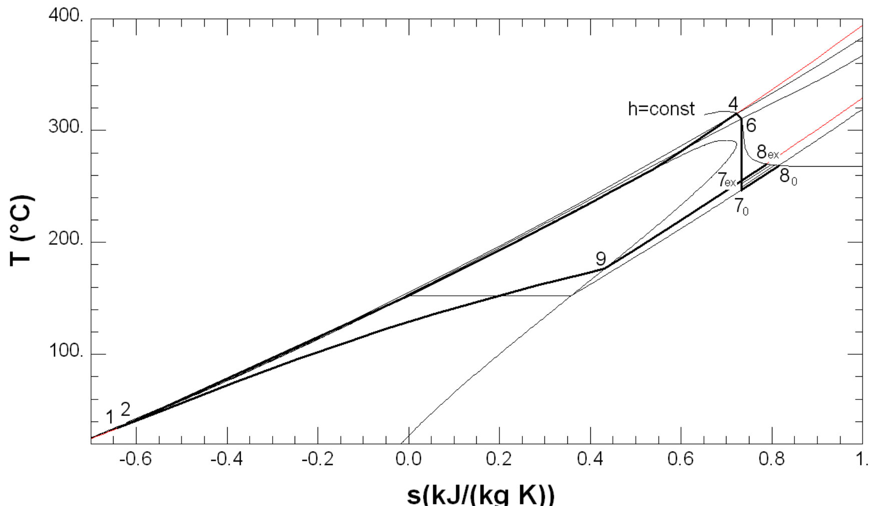


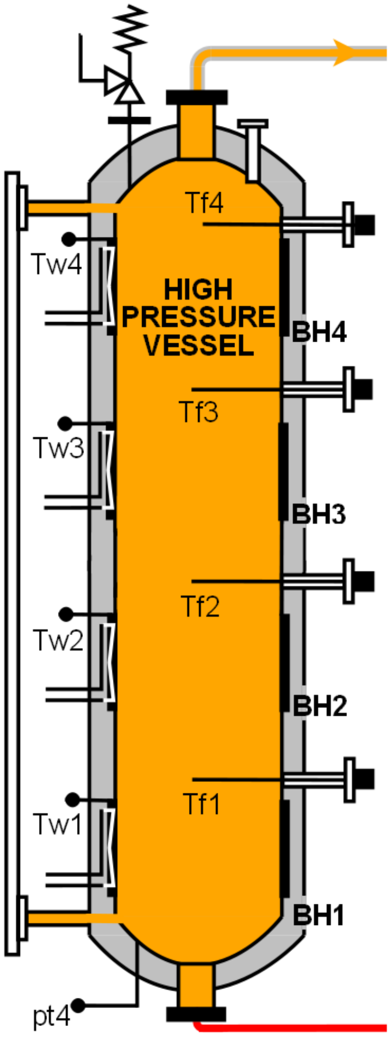


SELECTED CASES

	MDM_1	MDM_2	R245fa
$P_{T,4}$ (bar)	50	50	50
$T_{T,4}$ (°C)	315	311.4	176.5
$P_{T,6}$ (bar)	25	10	37
$T_{T,6}$ (°C)	310	276.9	159.2
P_7 (bar)	1	1	2
T_{cond} (°C)	40	40	40



Models – Heating system

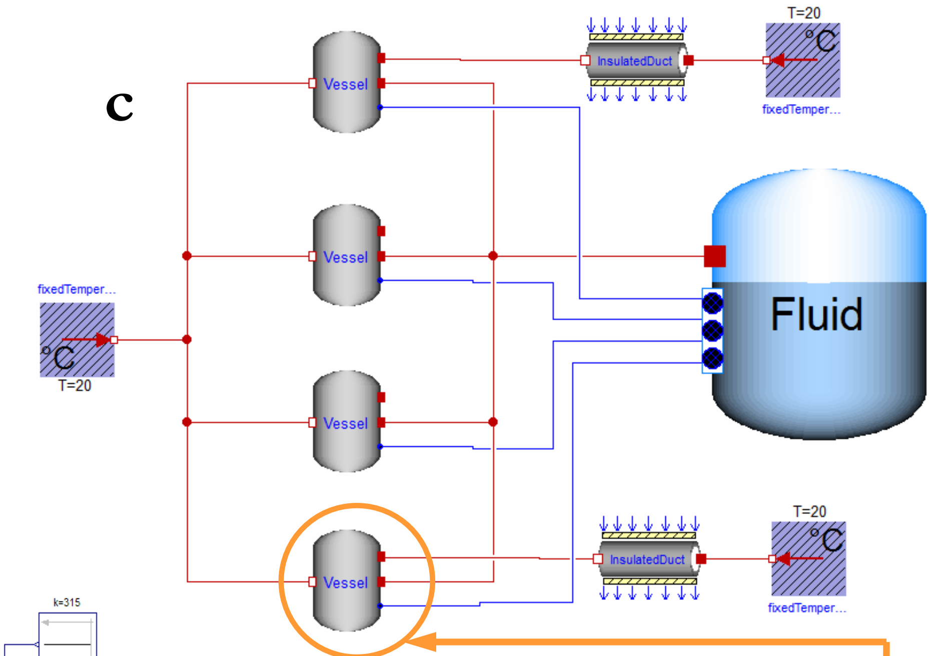


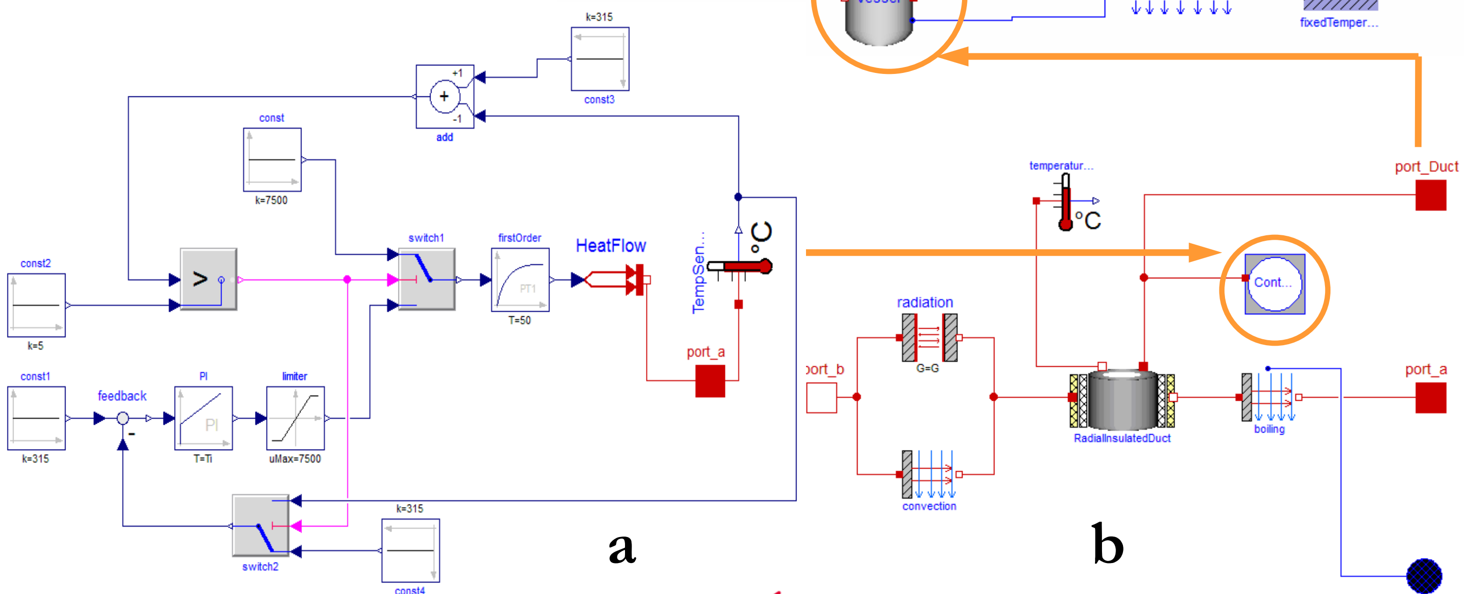
3 LEVELS

a. Control system model

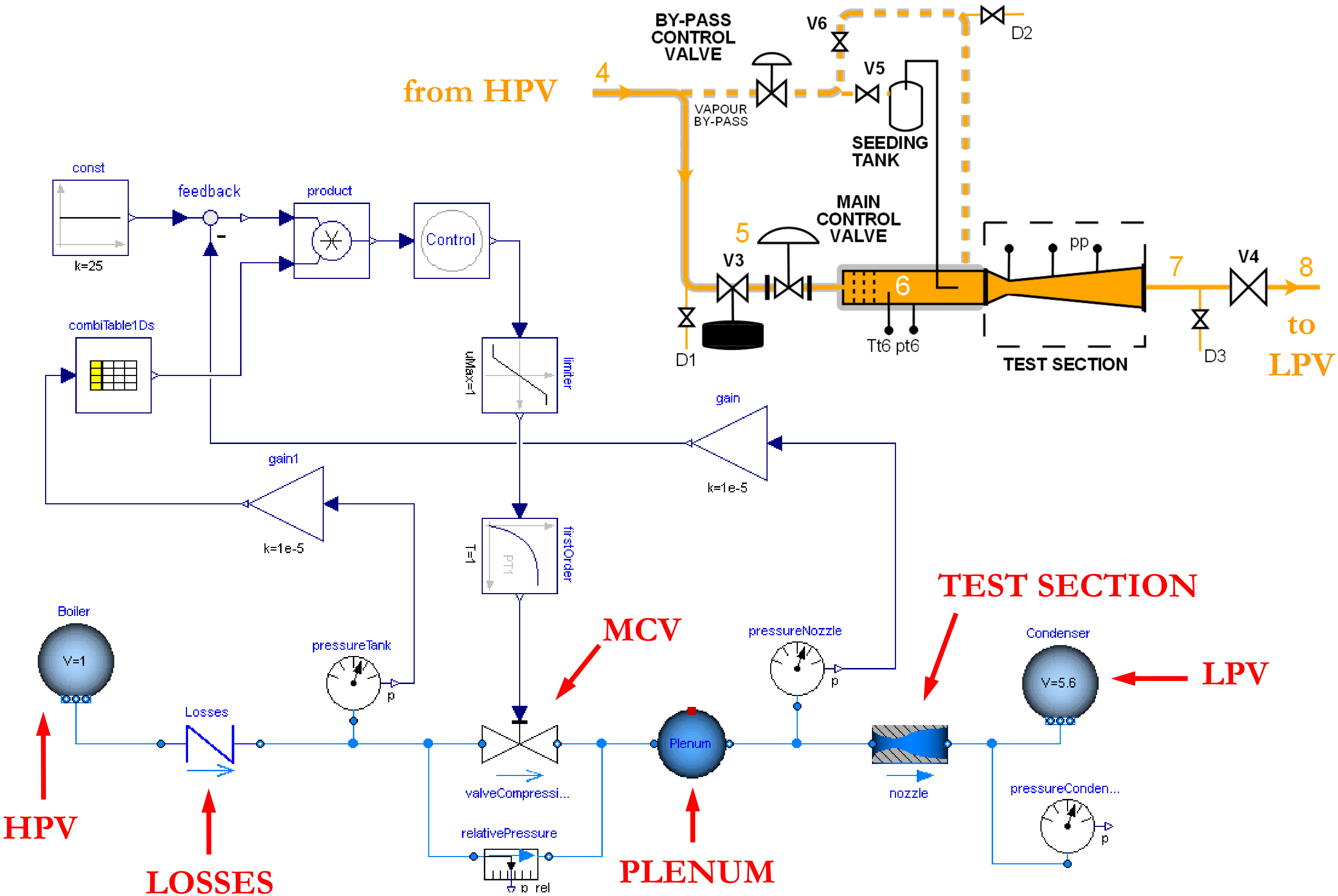
b. Vessel model

c. Heating system model





Models – Test system



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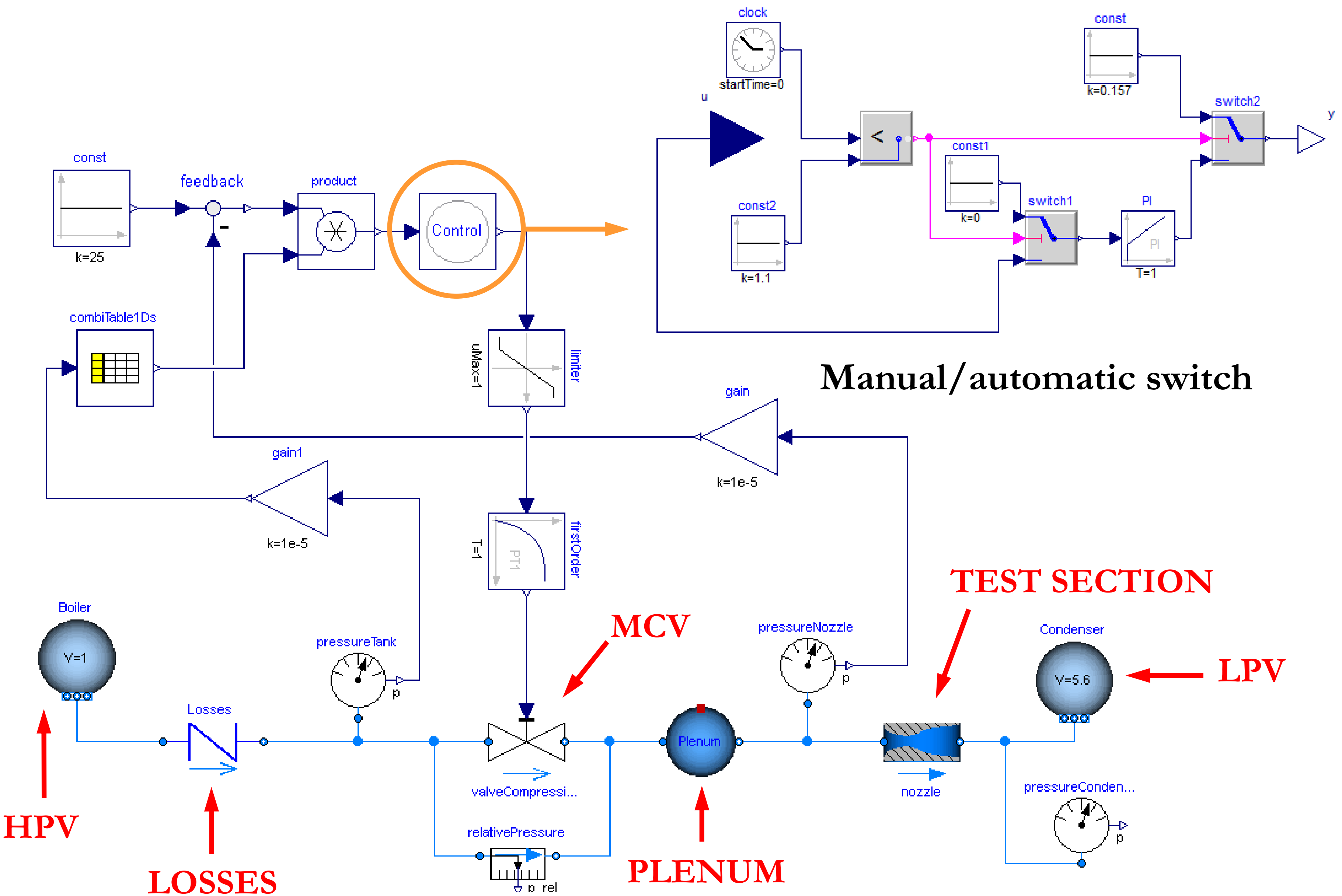
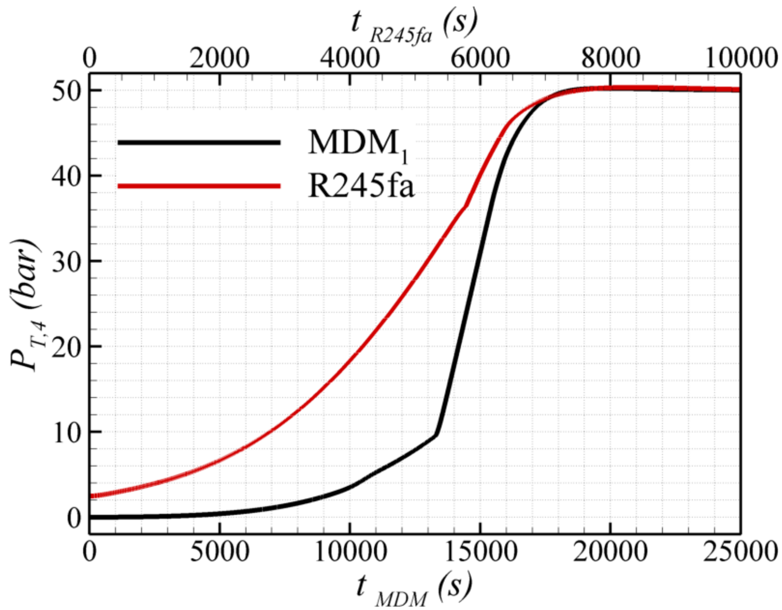
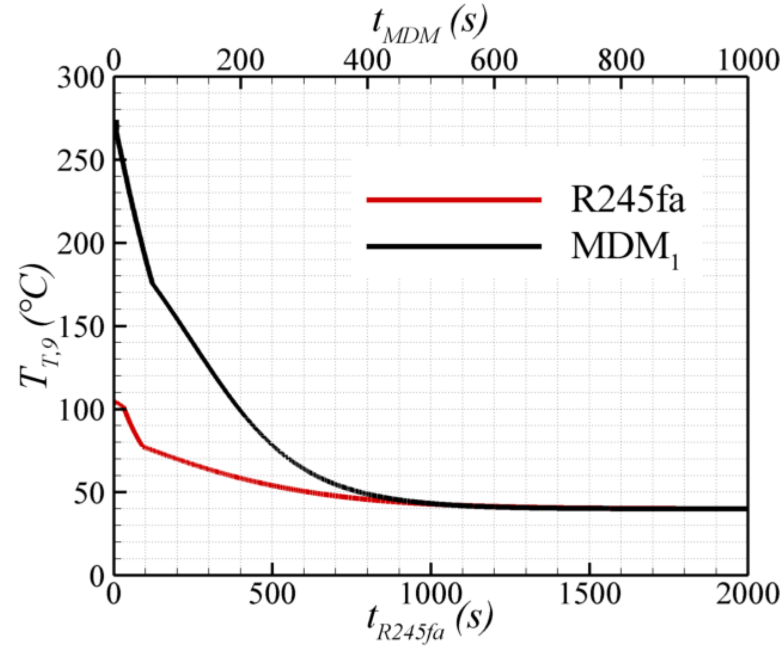


Simulation results: heating & condensing systems



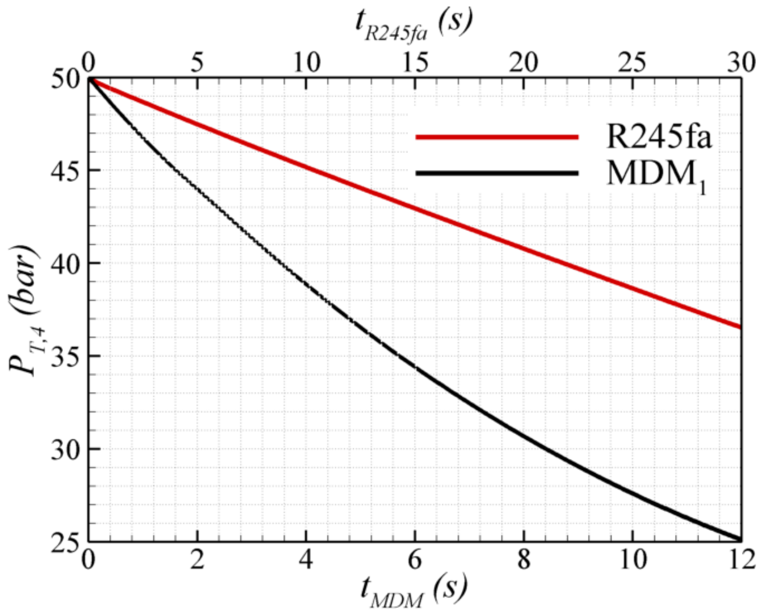


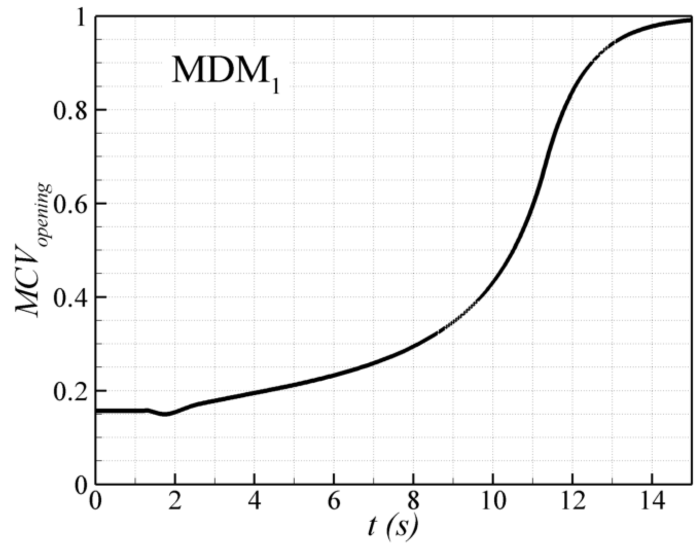
FINAL CONDITIONS

	MDM_1	MDM_2	R245fa
$P_{T,4}$ (bar)	50	50	50
$T_{T,4}$ (°C)	315	311.4	176.5
$\rho_{T,4}$ (kg/m^3)	372.9	364.0	498.2
$t_{heating}$ (s)	25000	25000	10000

	MDM_1	MDM_2	R245fa
P_{T9} (bar)	0.012	0.012	2.51
T_{T9} (°C)	40	40	40
P_{T6} (bar)	25	10	37
t_{cond} (s)	1000	1500	2000

Simulation results: test





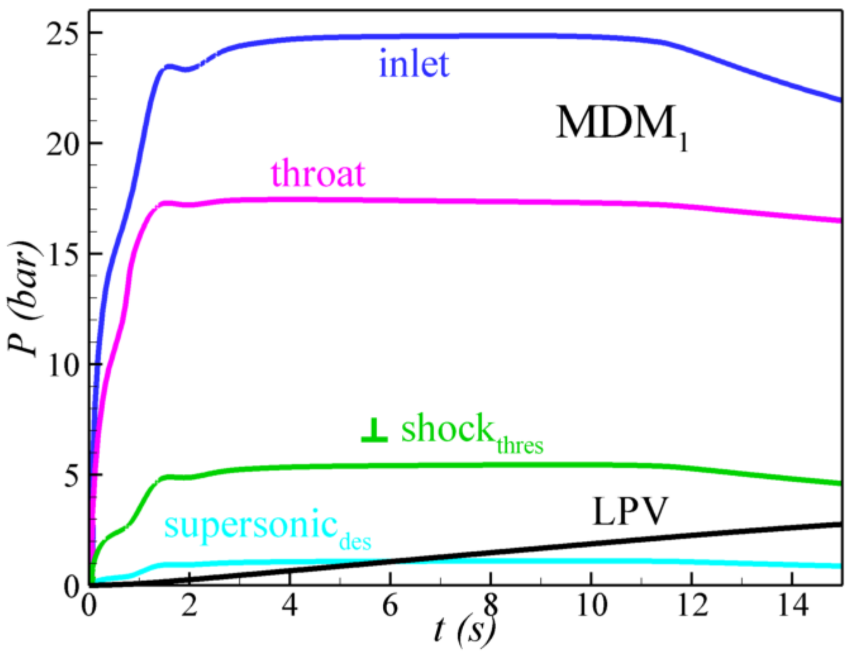
FINAL CONDITIONS

	MDM_1	MDM_2	R245fa
$P_{T,4}$ (bar)	25	17.7	37
$T_{T,4}$ (°C)	308	302.5	158.1
$P_{T,9}$ (bar)	2.27	4.44	8.33
$T_{T,9}$ (°C)	275	277	104.8
$P_{T,6}$ (bar)	25	10	37
M_{dis} (kg)	75	149	156
t_{ex} (s)	$\boxed{12}$	$\boxed{93}$	$\boxed{28.6}$

Simulation results: nozzle regimes

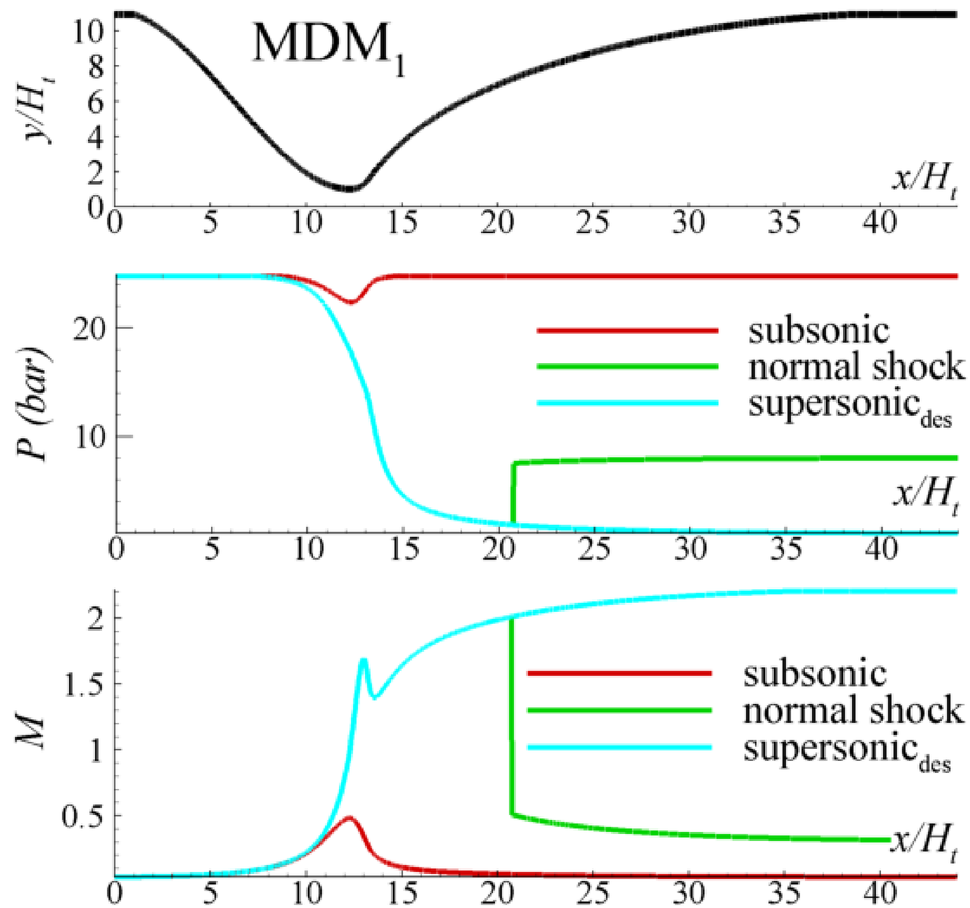
Lumped parameter
dynamic simulation – *Modelica*

Different regimes in time



Quasi 1-D steady calculation
at different P_8

Different regimes in space



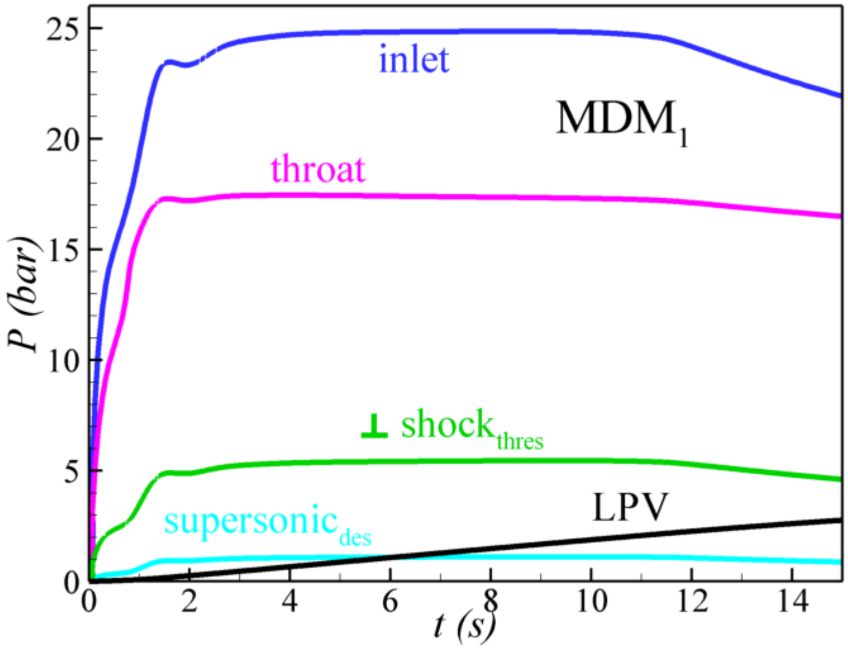
Simulation results: nozzle regimes

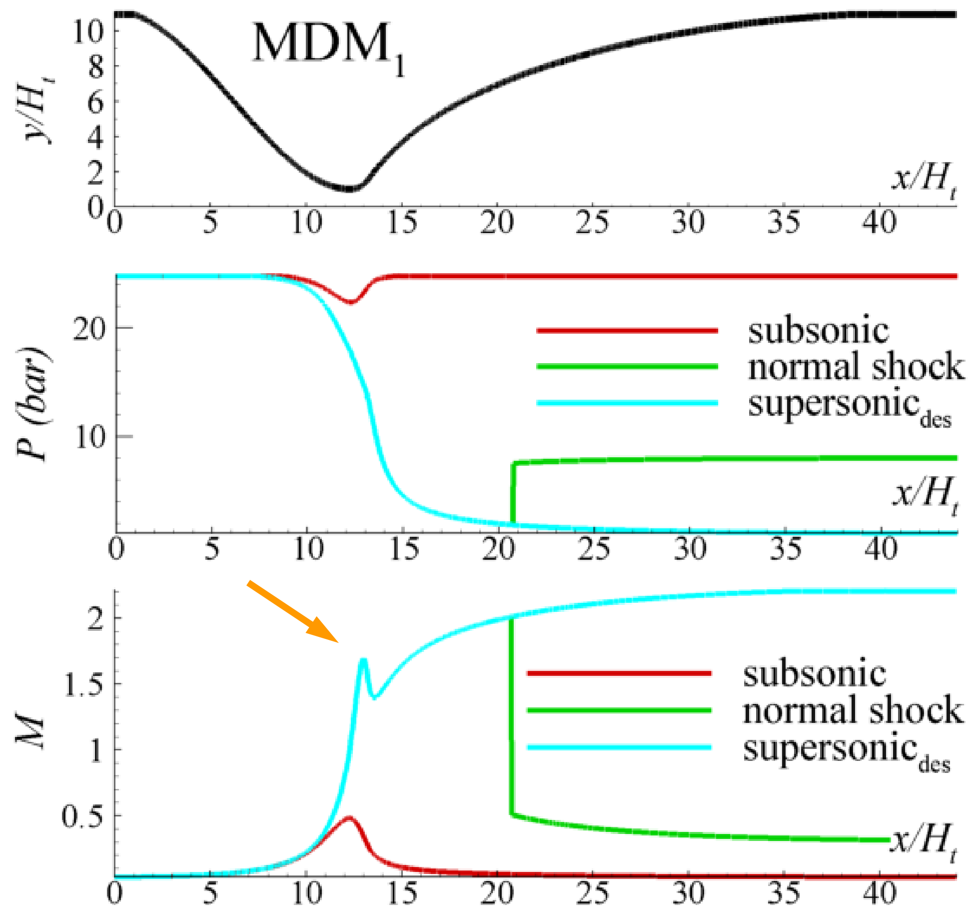
Lumped parameter
dynamic simulation – *Modelica*

Different regimes in time

Quasi 1-D steady calculation
at different P_8

Different regimes in space





$$\Gamma = 1 + \frac{\rho}{c}\left(\frac{\partial c}{\partial \rho}\right)_s < 1$$

→ Background on ORC

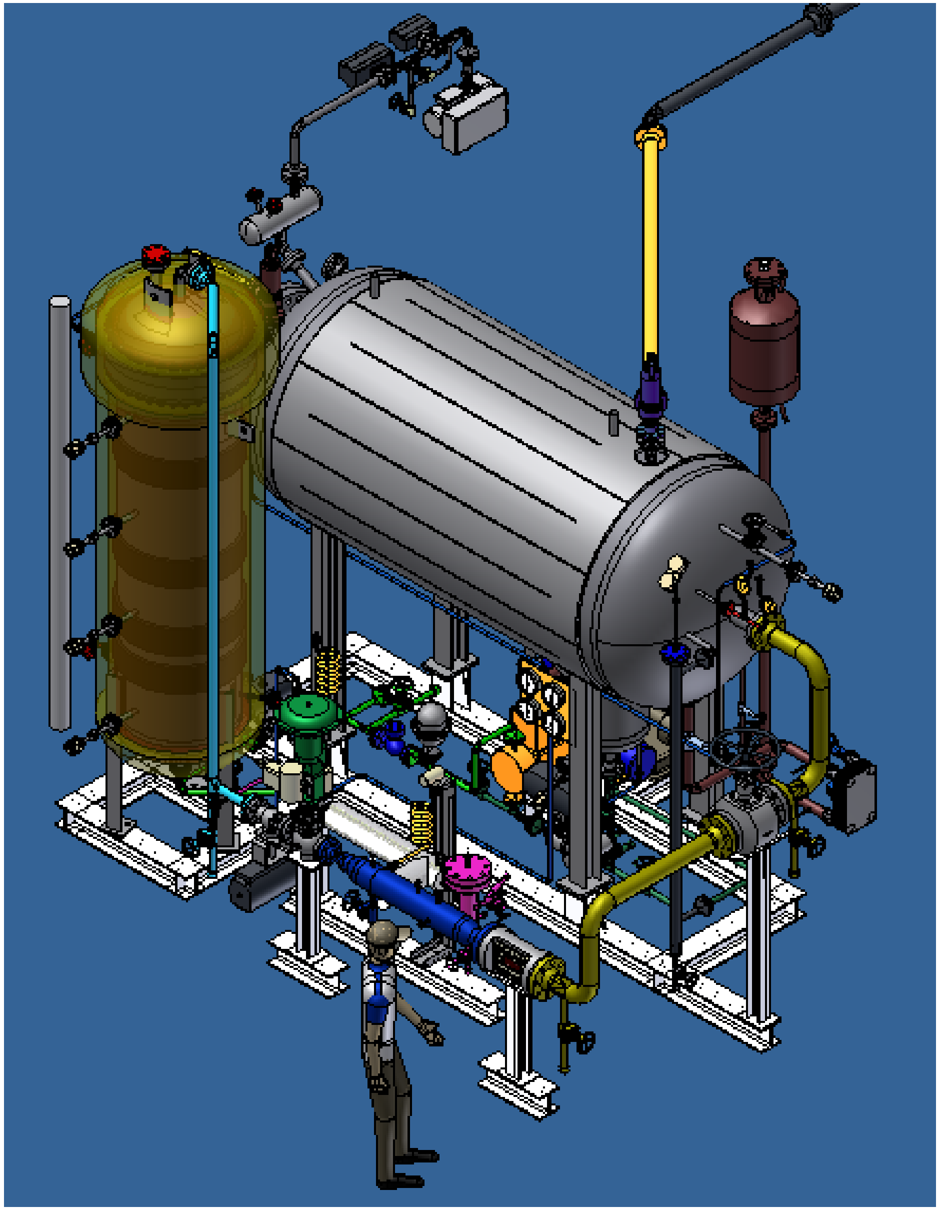
→ Design of the TROVA

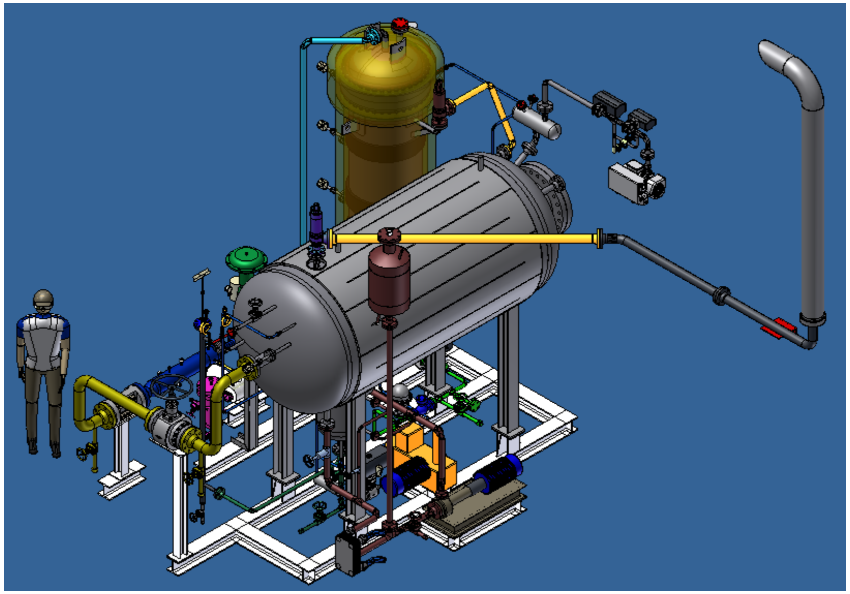
→ Dynamic simulation of the TROVA

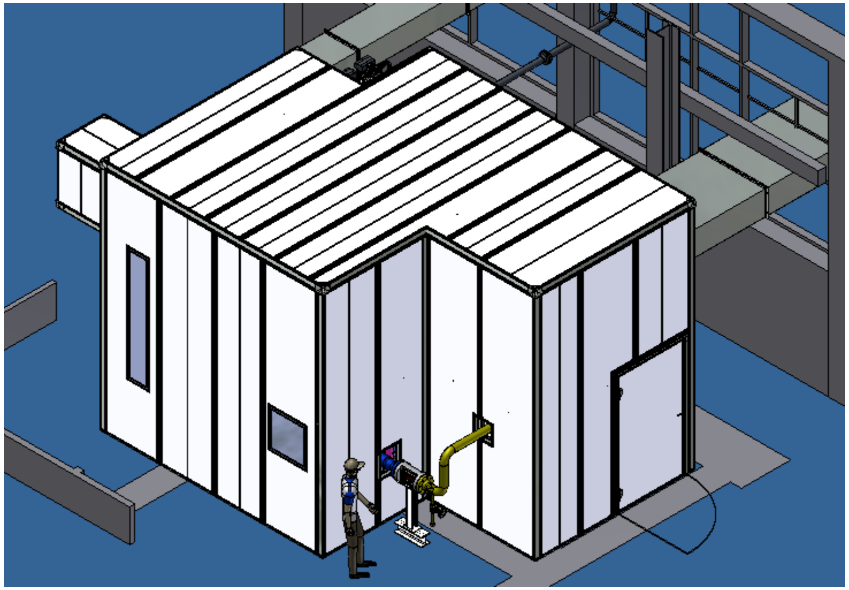
→ **Construction of the TROVA**

→ Conclusions

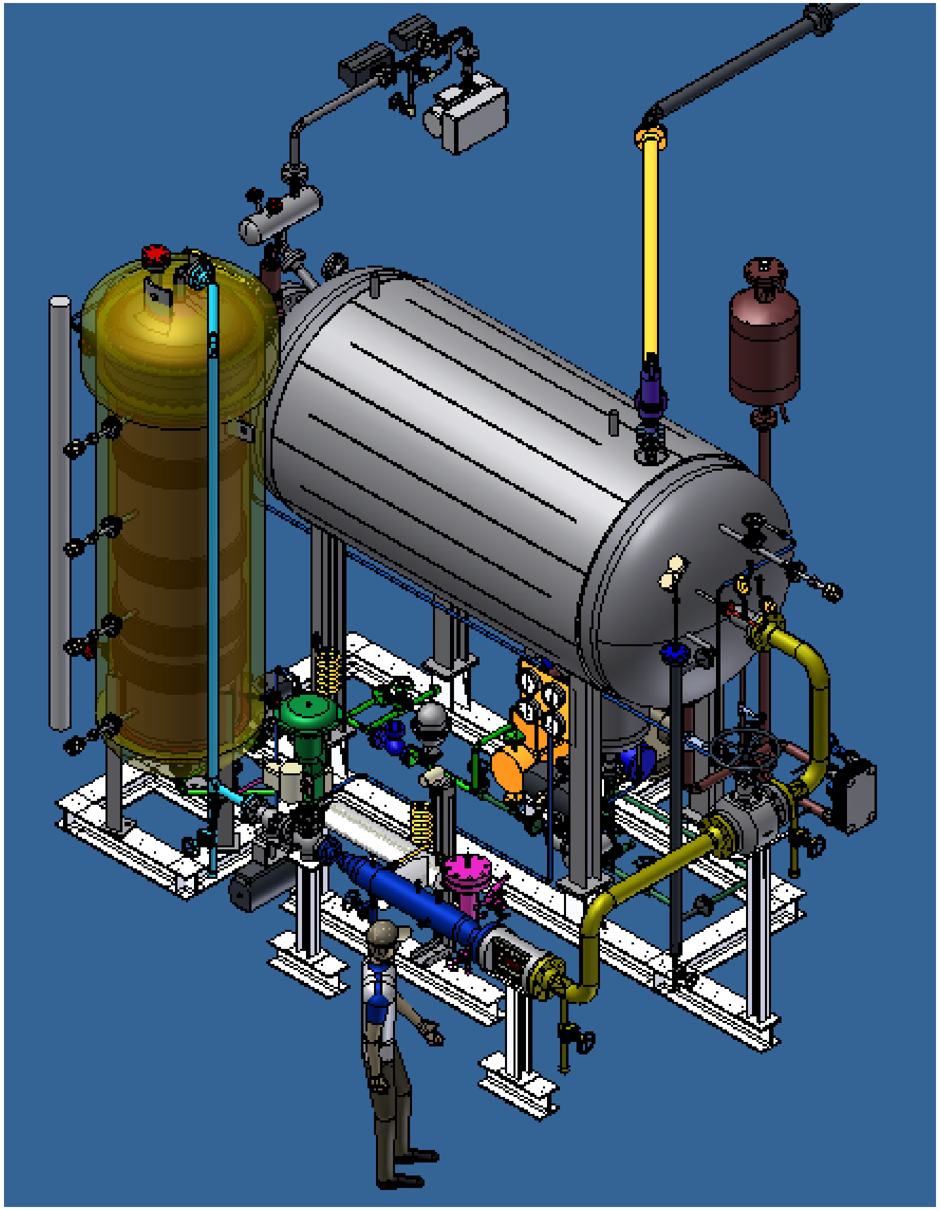
TROVA 3D layout & construction







TROVA 3D layout & construction



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clean energy ahead TURBODEN A PRATT & WHITNEY POWER SYSTEMS COMPANY

POLITECNICO DI MILANO

Conclusions

- Experimental investigation on typical ORC turbine expansions
  → flow caracterization – code validations
- Measurements in industrial ORC turbines: limits – needs of calibrated probes
- TROVA: bolw-down – phase transition facility
- Design & simulation → performance of proposed investigation
- Construction
- Conceived for ORC fluids/applications – other applications in real gases
  → real gases calibration tunnel

Developments

- Control + DAQ software
- Commissioning → **TEST**

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FLUID-DYNAMICS OF TURBOMACHINES

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- Profs Gianfranco Angelino & Costante Invernizzi

Energy Department

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THANK YOU FOR YOUR ATTENTION