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Faculty of Mechanical Science and Engineering, Institute of Power Engineering, Bitzer Chair of Refrigeration, Cryogenics and Compressor Technology

Expansion vessel for supercritical hydrogen in a spallation neutron source moderator circuit

M. Klaus[a], S. Eisenhut[a], Ch. Haberstroh[a], H. Quack[a], Y. Bessler[b] [a] *Technische Universitaet Dresden, Dresden, Germany,* [b] *ZEA1 – Forschungszentrum Juelich, Juelich, Germany*

Motivation

Parahydrogen around 20 K and above critical pressure is a preferred moderating fluid for conditioning of cold neutrons. Heat loads demand recooling and circulation in a closed loop. The engineering challenge is to keep the pressure and temperature within tolerable levels for expected or sudden changes of the neutron heat load.

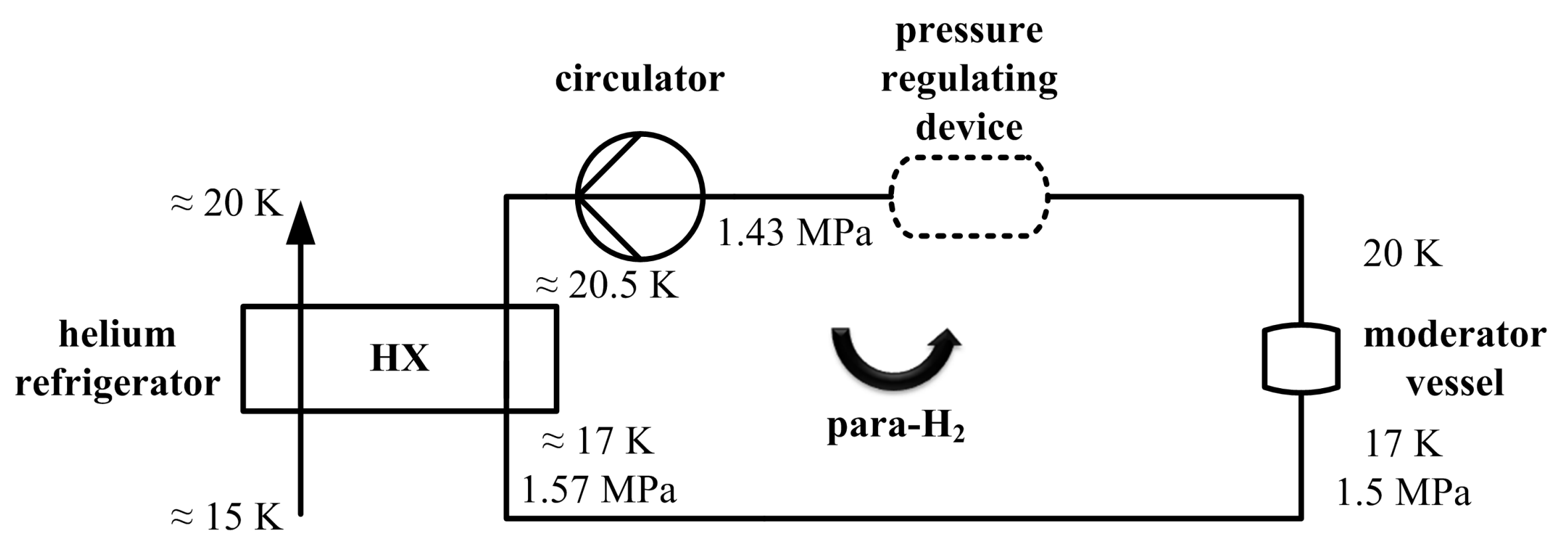

Figure 1. Simplified flow scheme of a moderator cooling circuit based on supercritical parahydrogen of a high-power spallation neutron source at 100 % beam power.

Pressure control possibilities

Hydrogen acts almost as an incompressible at temperatures around 20 K. Small variations in the mean temperature for a constant specific volume result in large pressure fluctuation in a rather short time.

There are three opportunities:

- Adjusting loop volume (ca. 1.2 %),
- Keep mean temperature constant (el. heater in LH$_2$ and/or energy balance over HX),
- Adjusting loop mass (ca. 1.2 %) by installing a small vertical vessel in a side arm.

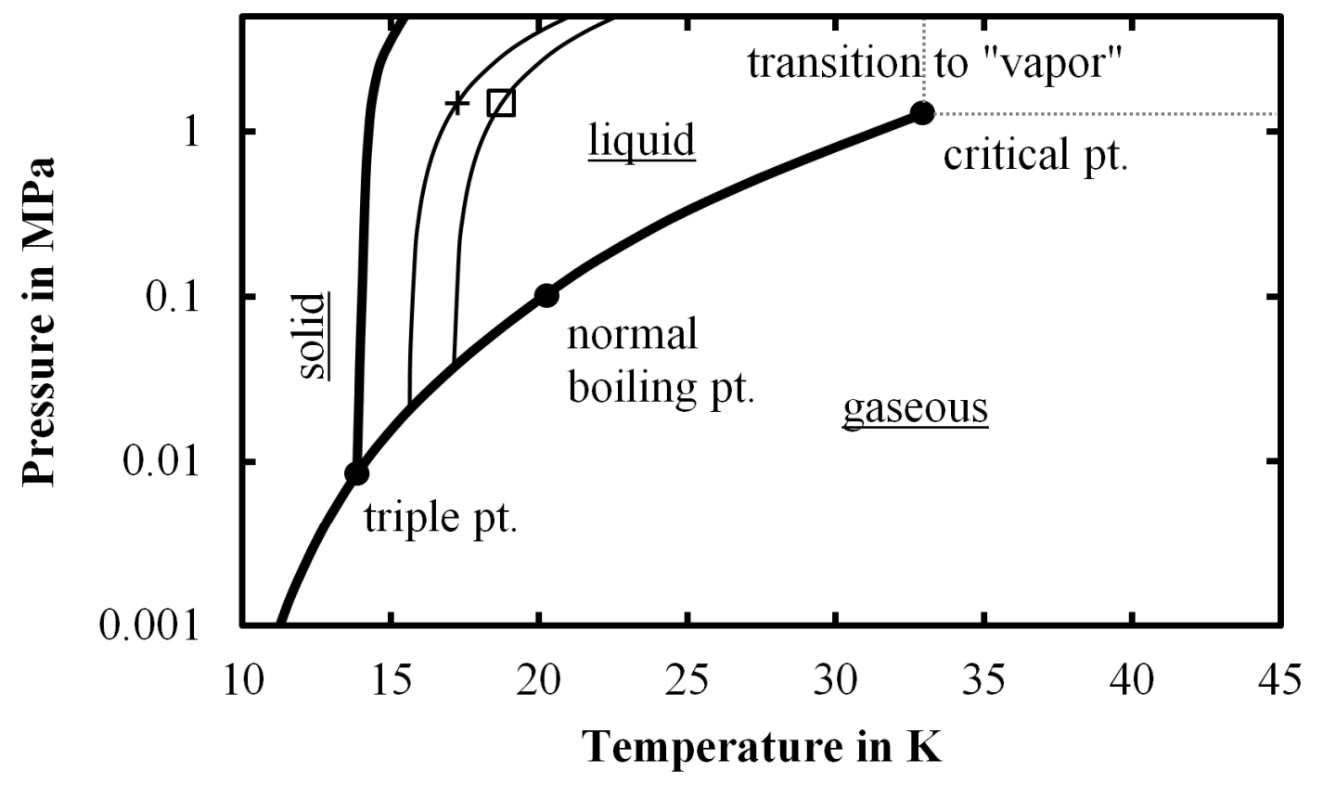

Figure 2. Phase diagram of parahydrogen.

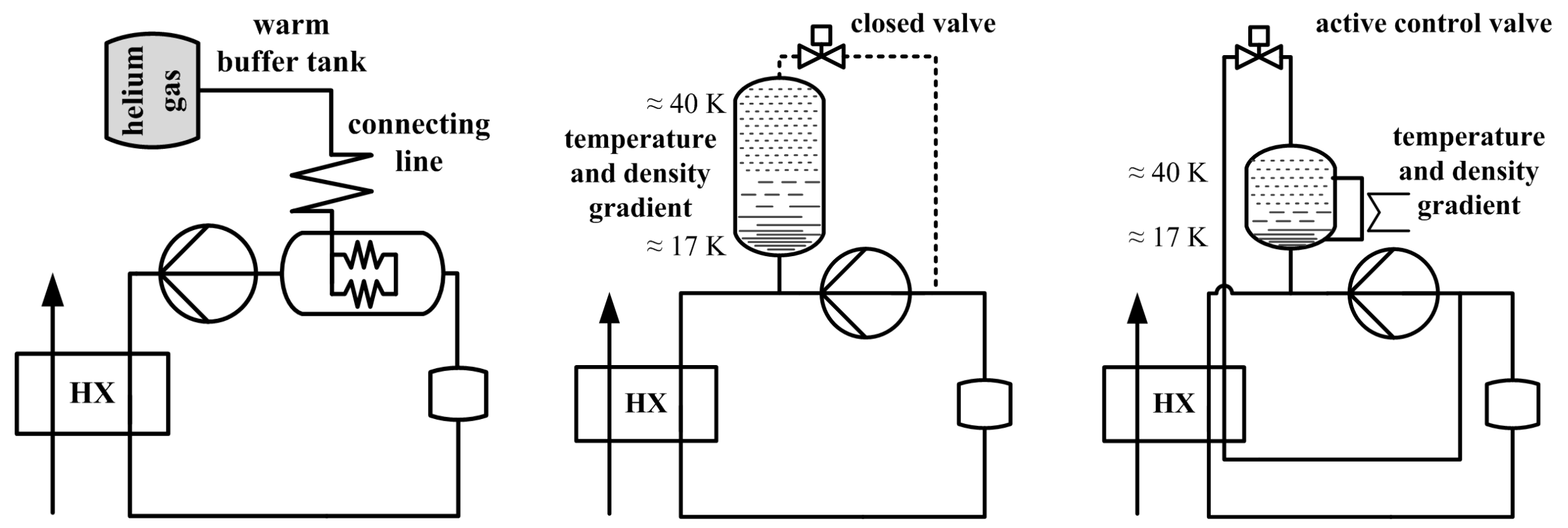

Figure 3. Helium gas-backed accumulator for volume variation (left), passive (middle) and actively controlled expansion vessel (right).

Contact details:
Technische Universitaet Dresden
Faculty of Mechanical Science and Engineering, Institute of Power Engineering
Bitzer Chair of Refrigeration, Cryogenics and Compressor Technology
MARCEL KLAUS
E-mail: marcel.klaus@tu-dresden.de
Phone 0049 351 463 39736

Passive expansion vessel

The vapor space at the top of the buffer acts as a gas spring dampening the pressure increase due rising mean loop temperature and inflow of 17.25 K liquid into the vessel.

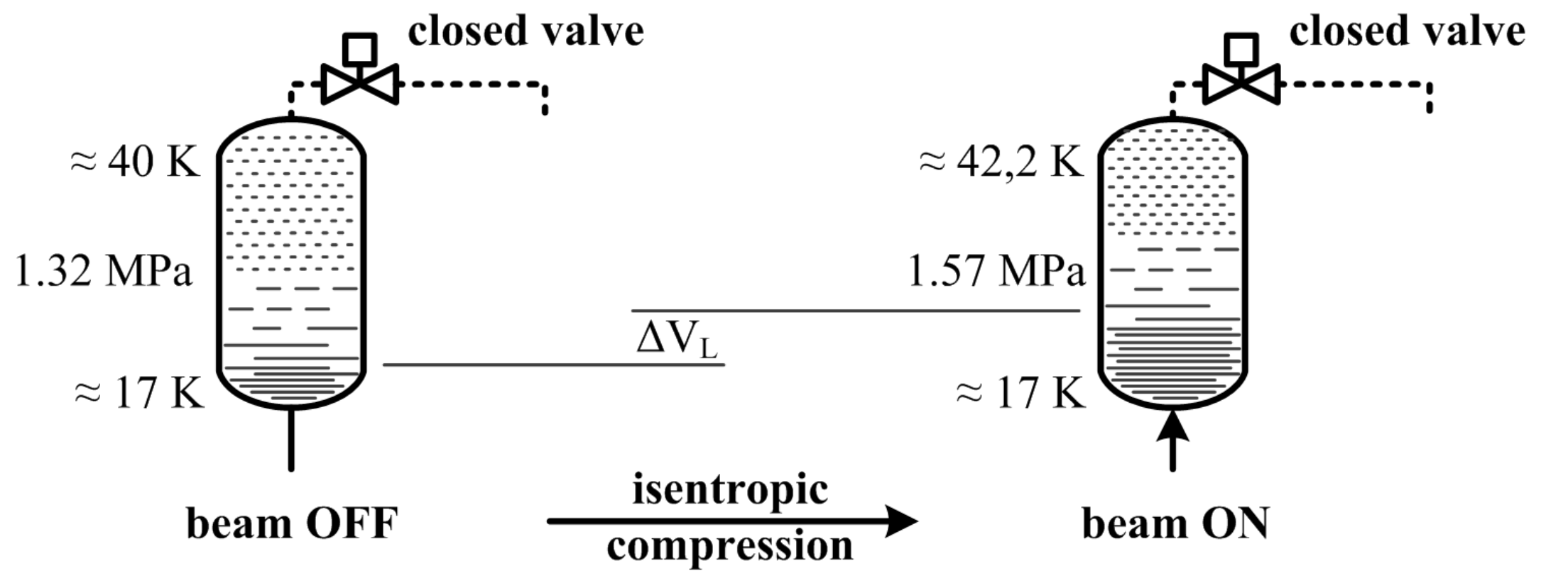

Figure 4. Passive expansion vessel (exemplary for a total volume of 60 L) with transition from beam OFF (left) to beam ON (right) and accompanied isentropic compression.

Table 1. Partial derivates for mean temperature change and pressure increase over loop.

p$_1$	T$_1$	v$_1$	p$_2$	T$_2$	v$_2$	$\left(\frac{\delta v}{\delta T}\right)_p$	$\left(\frac{\delta v}{\delta p}\right)_T$
MPa	K	m3/kg	MPa	K	m3/kg	m3/kg-K	m3/kg-bar
1.32	17.2	0.01328	1.32	18.4	0.01347	0.0001617	
1.32	18.4	0.01347	1.57	18.4	0.01342		0.0001840

Table 2. Isentropic compression of 40 K vapor.

state	P	T	s	v	$\left(\frac{\delta v}{\delta p}\right)_s$
[-]	MPa	K	kJ/kg-K	m^3/kg	m^3/kg-bar
OFF	1.32	40.00	16.60	0.0967	-0.033801
ON	1.57	42.82	16.60	0.0883	

Isentropic compression for 17.25 to 18.75 K, 300 L inventory and a buffer volume of 60 L (85 % vapor) results e.g. in a pressure rise of 0.25 MPa.

Actively controlled expansion vessel

The combination of liquid inflow and simultaneous outflow of seven times less dense vapor from the top of the vessel back to the loop enables an almost steady pressure for mean temperature variations.

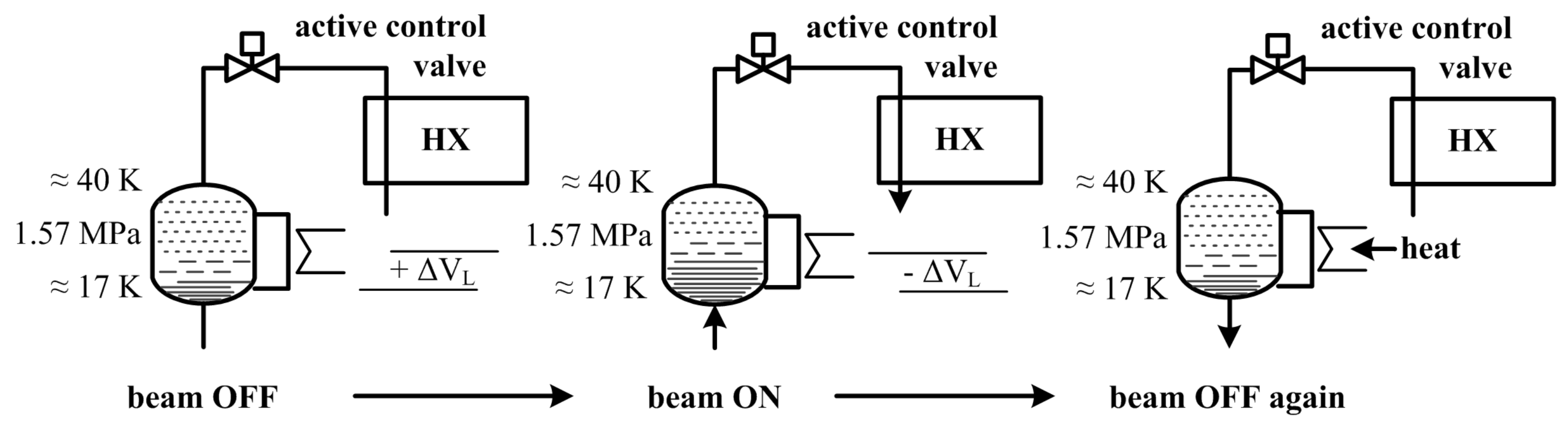

Figure 5. Active expansion vessel: transition from beam OFF (left) to beam ON (middle) and open control valve for vapour release and cool-down to pump suctions side; transition from beam ON (middle) to beam OFF (right) and necessary heating to re-establish vapour fraction.

To push back liquid out to the loop a heater (e.g. thermosiphon) has to restore the vapor volume with decreasing mean loop temperature. This vessel can be much smaller compared to the passive version but requires valve and heater control.

$$\Delta V_L = \frac{V_L \cdot (\bar{v}_{ON} - \bar{v}_{OFF})}{\bar{v}_{OFF}} \qquad \dot{m}_L = \frac{V_L^3 \cdot (\bar{v}_{ON} - \bar{v}_{OFF})}{\bar{v}_{OFF}^2 \cdot 2\dot{V}_{pump}} \qquad \dot{m}_V = \frac{\Delta V_L \cdot v_V \cdot V_L}{2\dot{V}_{pump}}$$

Table 3. Change of mean specific volume for actively controlled vessel.

state	p$_1$	T$_1$	v$_1$	p$_2$	T$_2$	v$_2$	v_mean
[-]	MPa	K	m^3/kg	MPa	K	m^3/kg	m^3/kg
OFF	1.57	17	0.01320	1.57	17.5	0.01328	0.01324
ON	1.57	17	0.01328	1.57	20.5	0.01380	0.01354

Numerical approach

The ideal process of isentropic compression of the 40 K vapor space does not take into account the compressible feature of the transition zone, heat conduction or mixing effects. Therefore a CFD simulation was set up. High resolution table based hydrogen property data allow numerical calculations in the range between 1.3 to 2 MPa and 16 to 100 K. Compared to the isentropic compression the pressure increase in the CFD simulation is smaller because of taking into account the compressible transition zone and forced mixing due to the incoming flow of cold hydrogen.

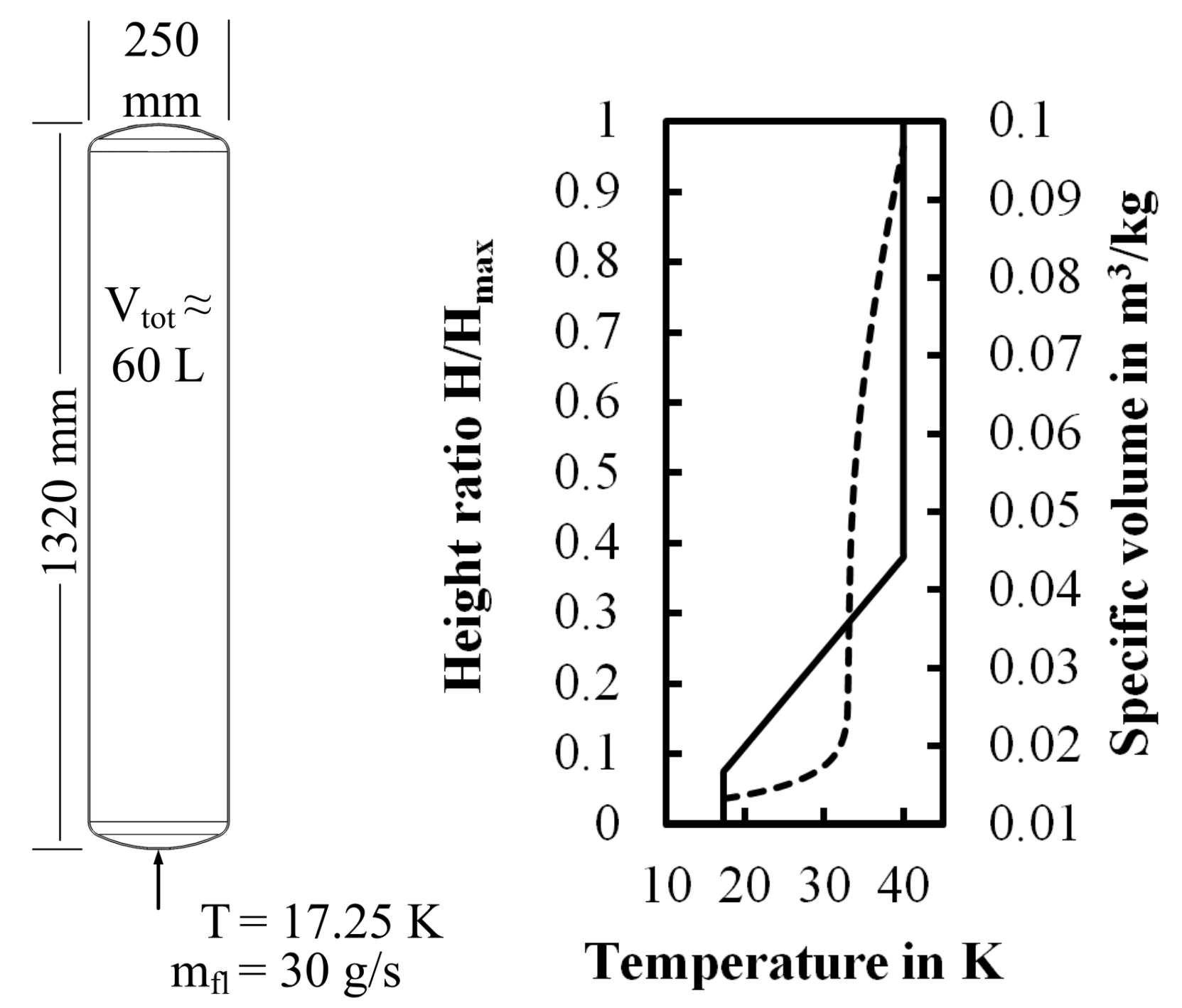

Figure 6. Geometry, initial horizontal temperature profile and respective specific volume (dotted line) for CFD calculations.

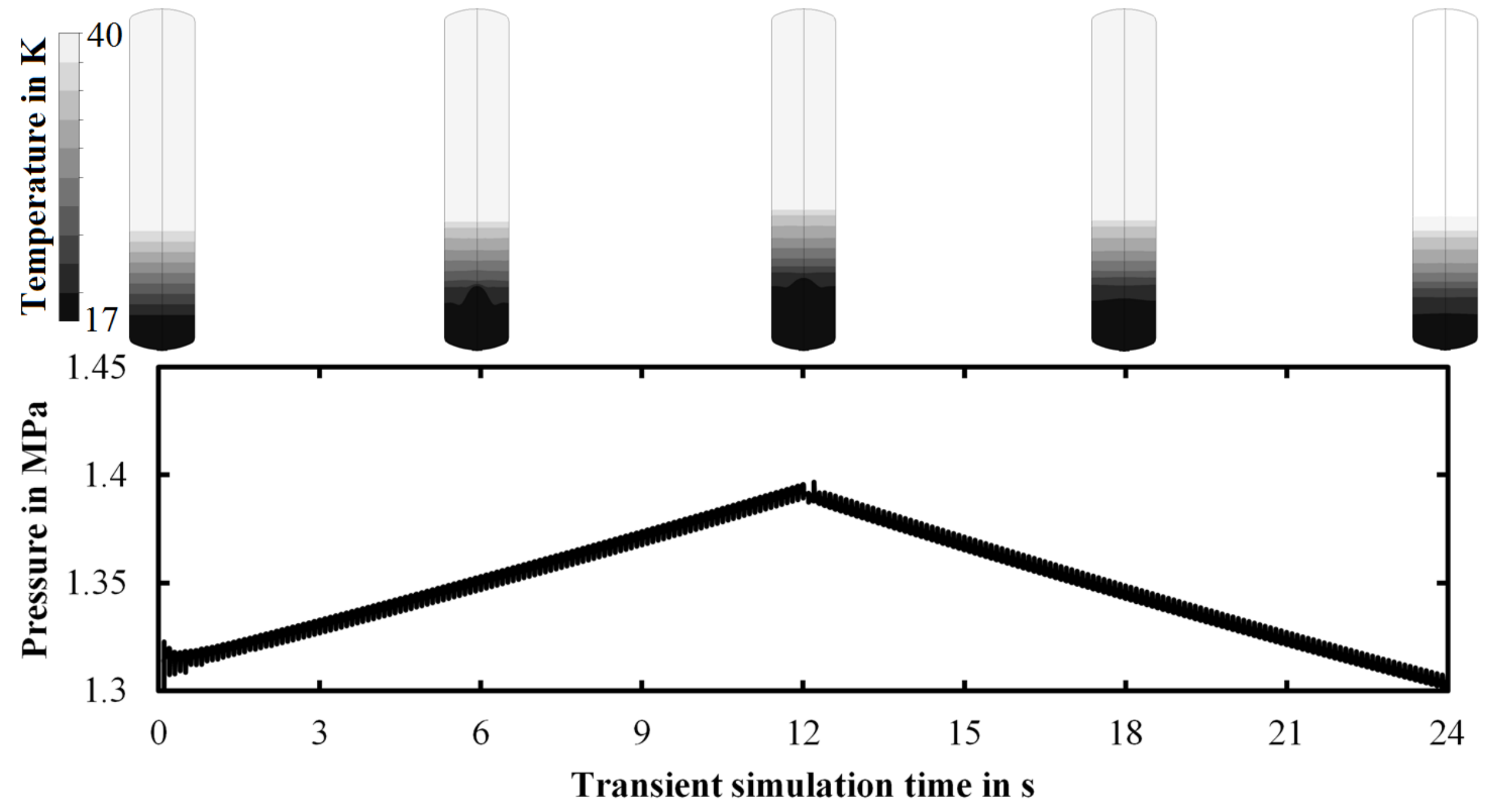

Figure 7. CFD simulation of inflow followed by outflow for the 60 L passive expansion vessel with transient pressure and temperature distribution.

CEC-ICMC 2015, 28 June to 2 July, Tucson, Arizona, United States; C1PoJ – Novel Concepts and New Devices