Thermal-Hydraulic Performance of Printed Circuit Heat Exchanger in Supercritical CO_2 Cycle

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Study Incentives

- Supercritical CO_2 cycle demonstrates some advantages in comparison to He cycle

  - higher cycle efficiency (Y. Kato, 2003),

  - better turbomachinery (Y. Muto, 2003),

  - power generation cost is expected to be smaller.

- High efficiency recuperator is a crucial component of supercritical CO_2 cycle. The targeted recuperator effectiveness is as high as 95%.

- PCHE is a promising heat exchanger because it

  - is able to withstand the pressure up to 50 MPa and the temperature up to 700^{o}C (reliability),

  - has a high compactness and high efficiency (cost reduction).

PCHE = Printed Circuit Heat Exchanger

What is the PCHE?

- ✓ **Fluid flow channels are etched chemically on metal plates.**

  - Typical plate: thickness = 1.6mm,

  width = 600mm, length = 1200mm,

  - Channels have semi-circular profile with 1-2 mm diameter.

- ✓ **Etched plates are stacked and diffusion bonded together to fabricate a block**

- ✓ **The blocks are then welded together to form the complete heat exchanger core**

Construction of PCHEs

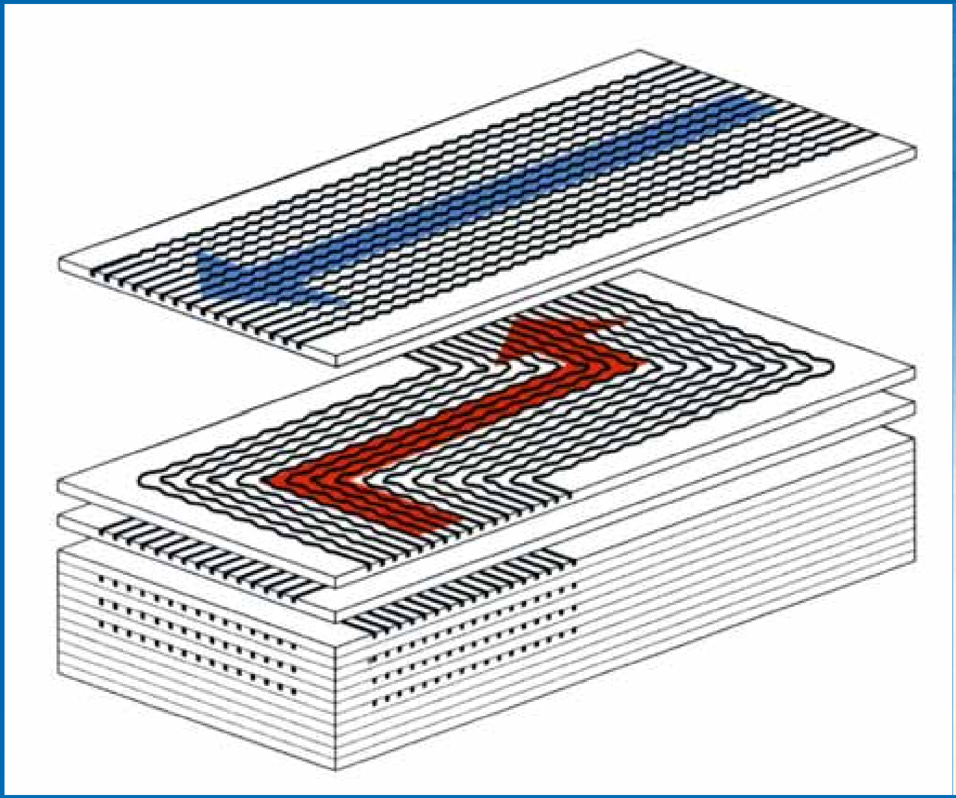
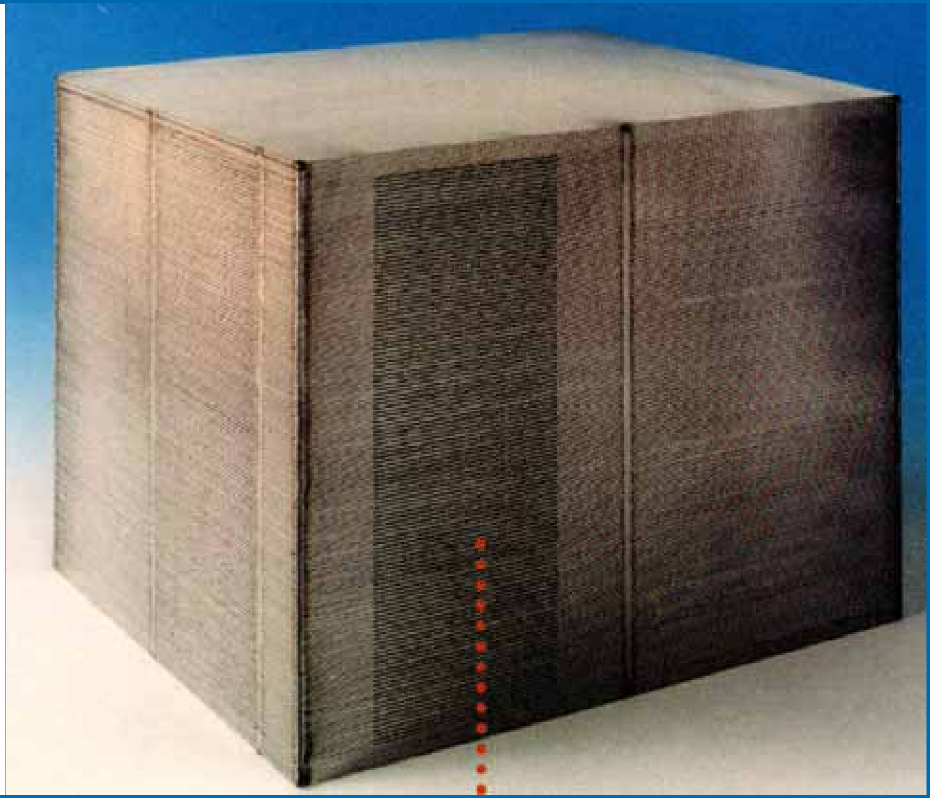


Plate stacking



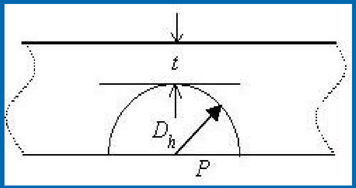
Diffusion bonding

the bond strength is achieved by pressure, temperature, time of contact, and cleanliness of the surfaces

Advantages of PCHE

- **Photo-etching technology:**
  - ➔ **Micro channels with smaller hydraulic diameter D_h:**
    - ⇨ **Pressure capability in excess of 50 MPa.**

$$\sigma = \frac{PD_h}{2t}.$$

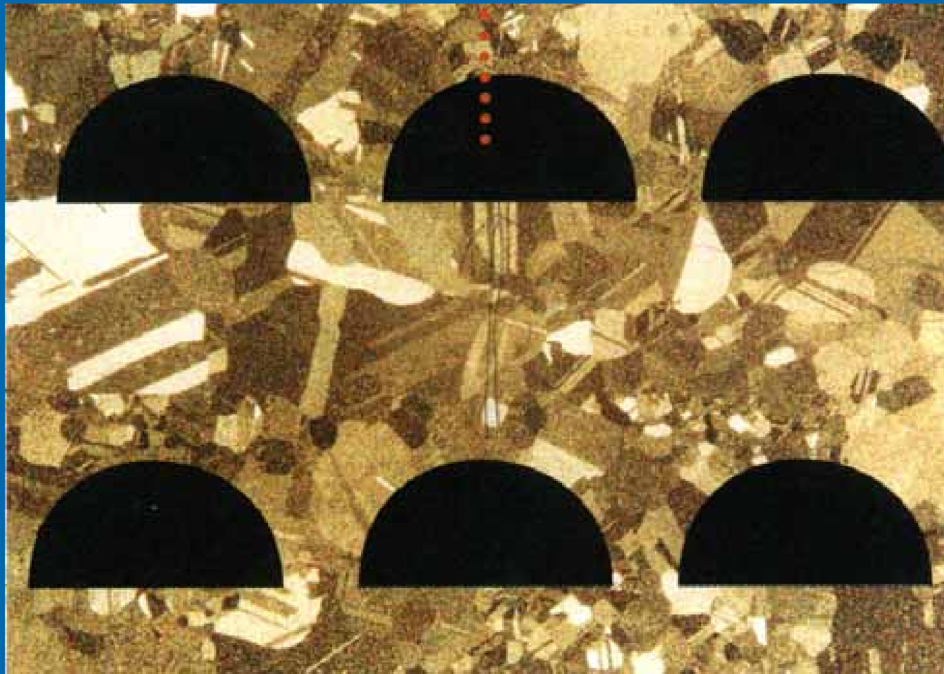


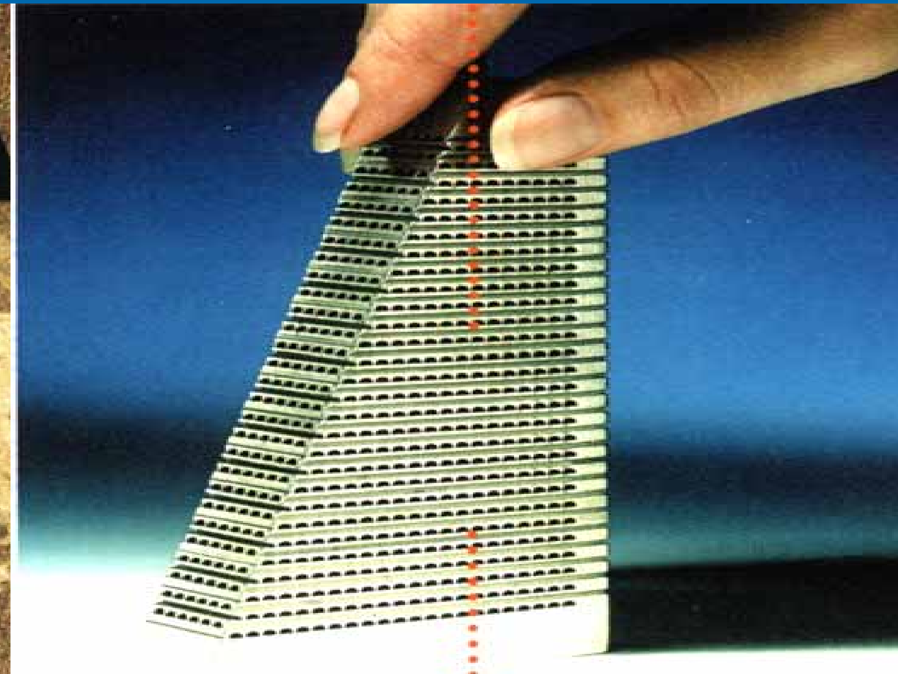
    - ⇨ **Compact size (L) or Higher efficiency (98%).**

$$L = \frac{D_h}{4j}\Pr^{2/3} N \quad \text{where} \quad N = \frac{(T_o - T_i)}{\Delta T_{LMTD}}.$$

  - ➔ **No plate-fin brazing:**
    - ⇨ **Manufacturing cost reduction.**

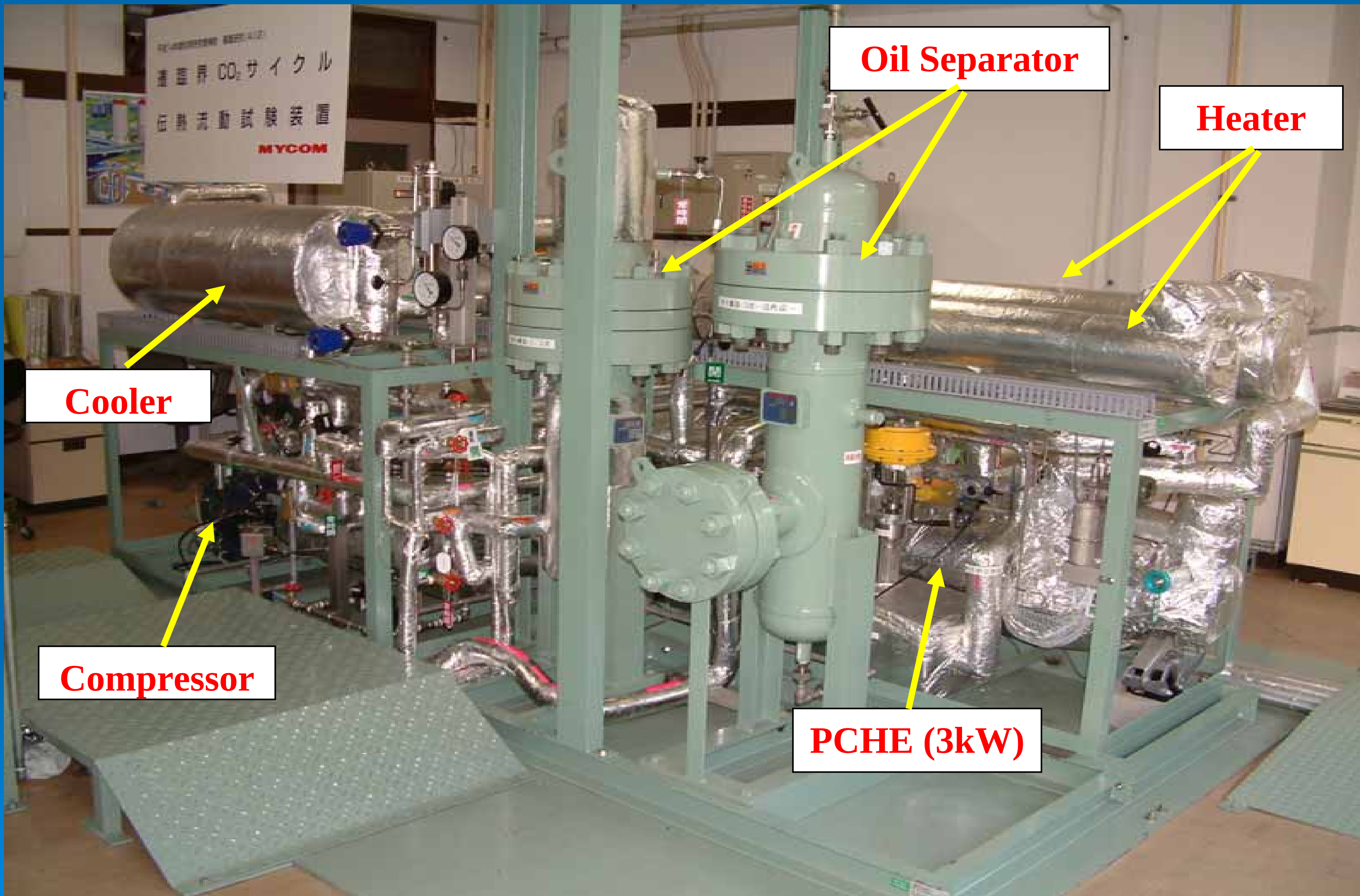
- **Diffusion bonding technology:**
  - ➔ **Maintain parent material strength:**
    - ⇨ **Extreme temperature from cryogenic up to 700^{o}C.**



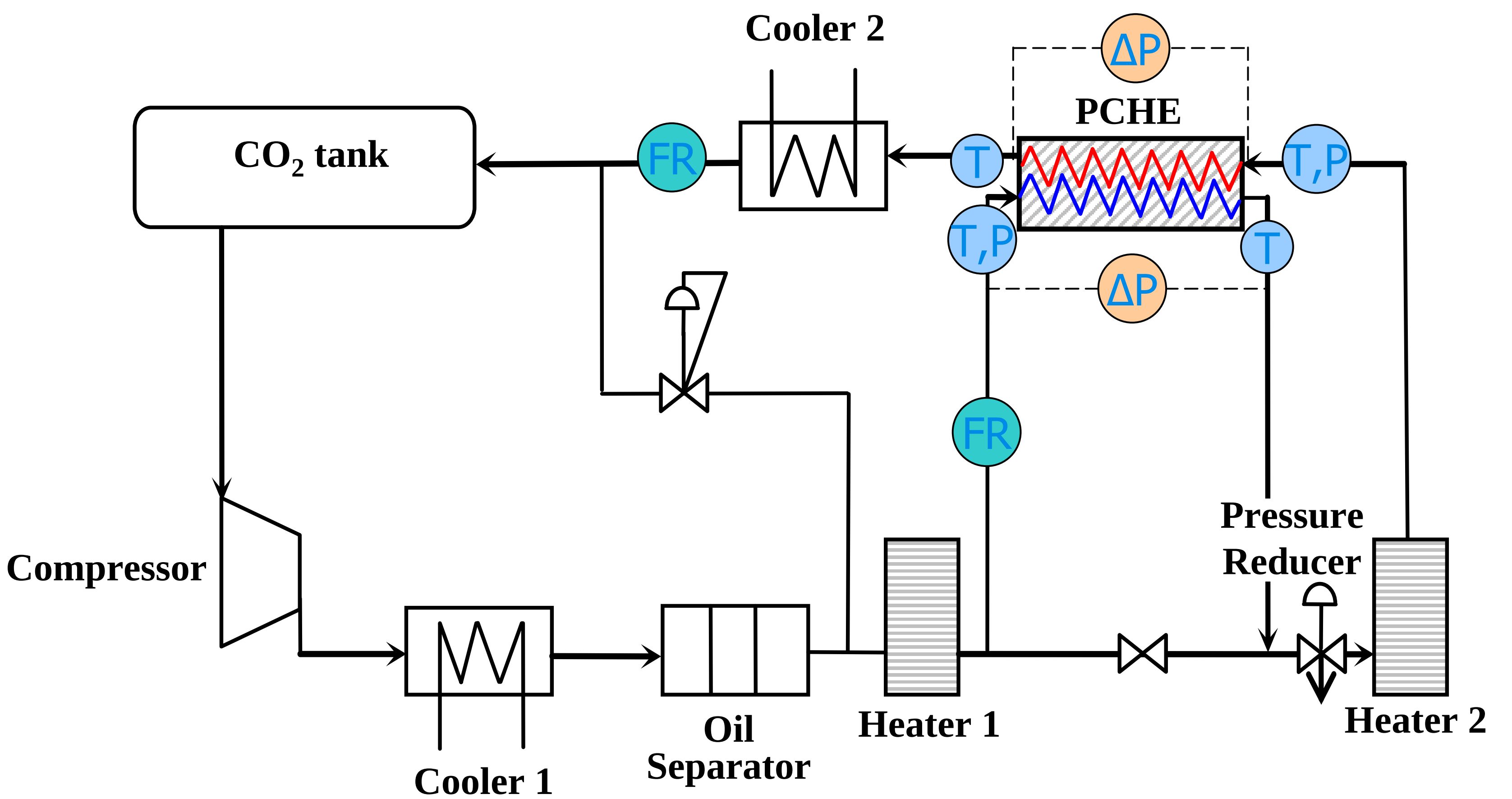


From HEATRIC homepage

Experimental Facility



Experimental Loop

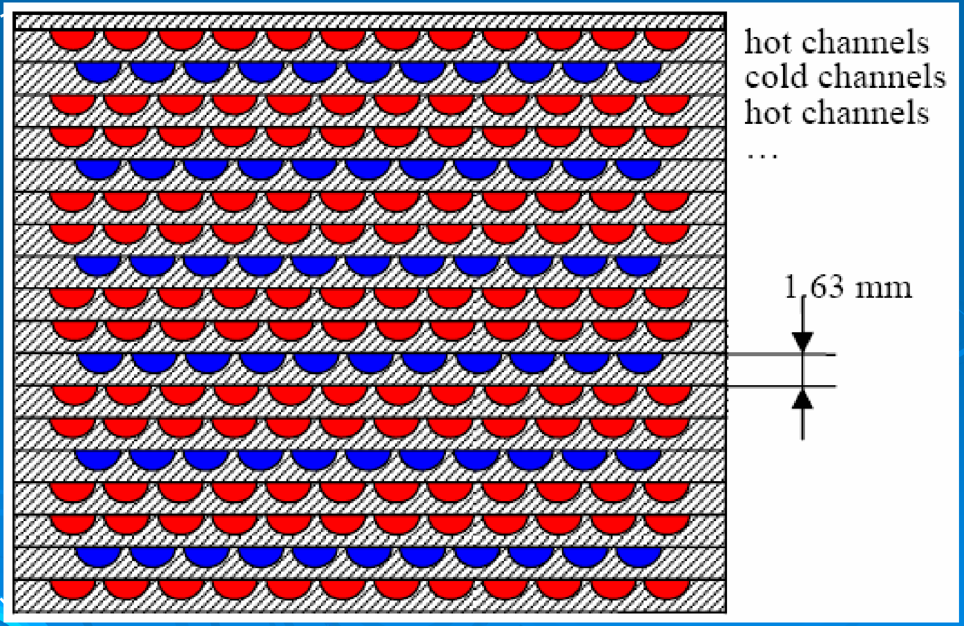


T :thermocouple, P :pressure meter, ΔP :differential pressure meter, FR : flow rate meter

PCHE Test Section

Dimension of 896 x 76 x 71 mm and a dry mass of 40 kg

	Channel geometry (mm)				Area, (m^2)	
	Channels number, n	Diameter, D	Active length, L	Hydraulic diameter, D_h	Heat transfer, A	Free flow, A_c
Hot side	144	1.69	1062	1.03	0.664	0.00016
Cold side	66	1.69	1170	1.03	0.336	0.000074



Experimental Conditions

No.		1	2	3	4	5
Pressure, MPa	Cold side	**6.5**	**7.4**	**8.5**	**9.5**	**10.2**
	Hot side	**2.2**	**2.5**	**2.8**	**3.0**	**3.3**
Temperature, °C	Cold side	**90-108**				
	Hot side	**280-300**				
Flow rate, kg/h	-	From **40 to 80** with 5 kg/h increment				

Overall Heat Transfer Coefficient, *U*

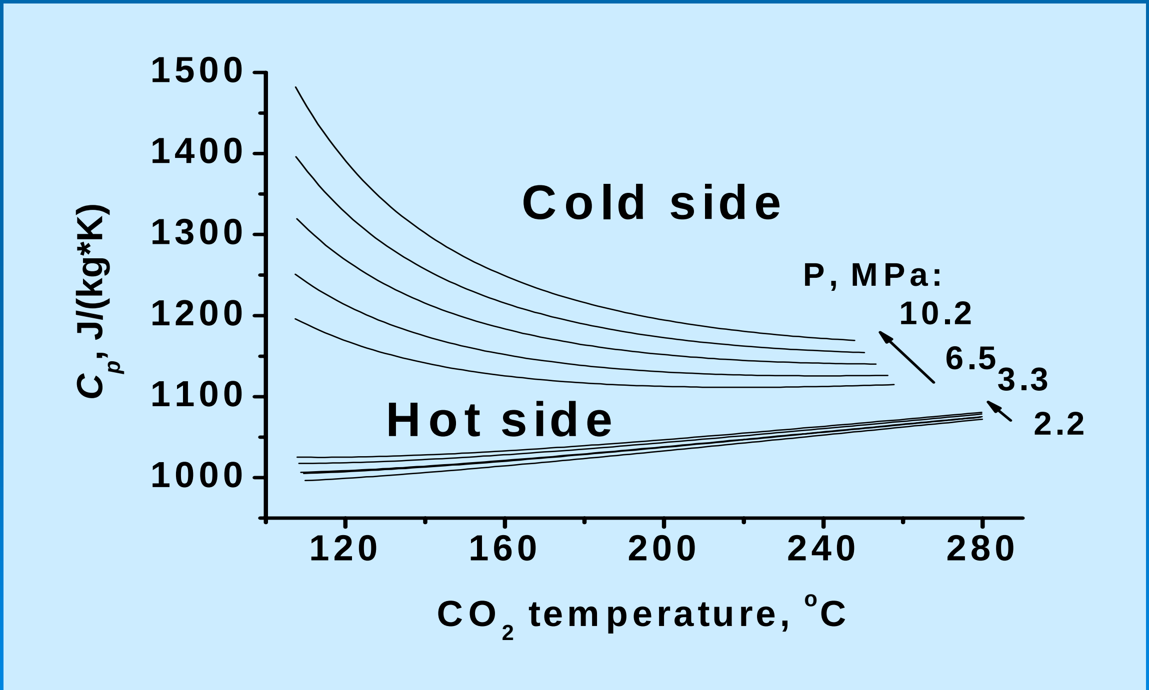
- **LMTD method:**

$$U = \frac{\frac{1}{2}\left(|Q_c| + |Q_h|\right)}{A_h F_G \dfrac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln\left[(T_{h,i} - T_{c,o})/(T_{h,o} - T_{c,i})\right]}}$$

where

$$Q_c = W_c(h_{c,o} - h_{c,i})$$

$$Q_h = W_h(h_{h,o} - h_{h,i})$$



A **- Heat transfer area, 0.664 m²**

F_G **- Geometric factor, 0.9624**

h, c **- hot, cold side**

o, i **- outlet, inlet**

Heat Loss Estimation (1)

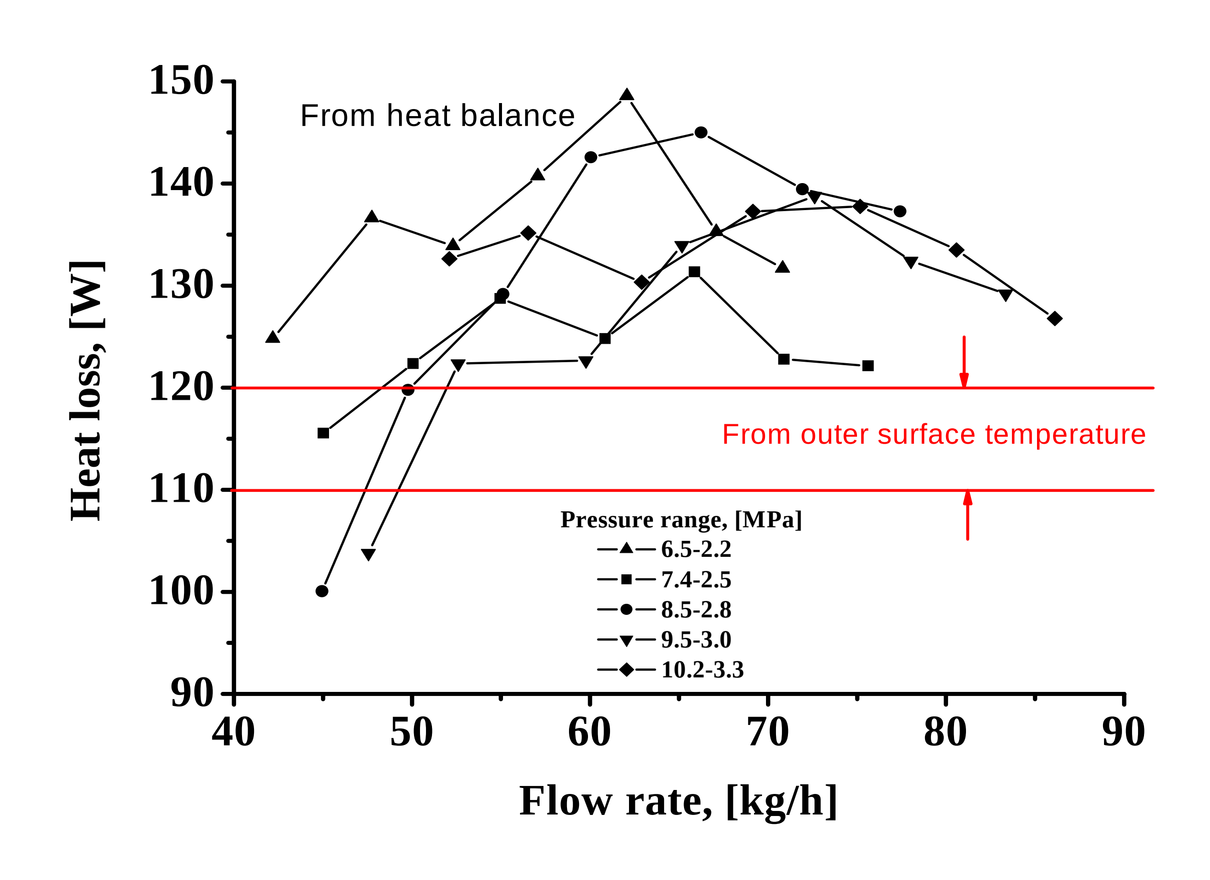
Total value:

1) **From outer surface temperature of PCHE insulator**

$$Q_{loss} = \sum_{i=1,10} A_i^{ins}\left[\varepsilon\sigma(T_{s,i}^4 - T_{surr}^4) + h_{conv,i}(T_{s,i} - T_{surr})\right] \approx 110 \sim 120\ [W]$$

2) **From heat balance**

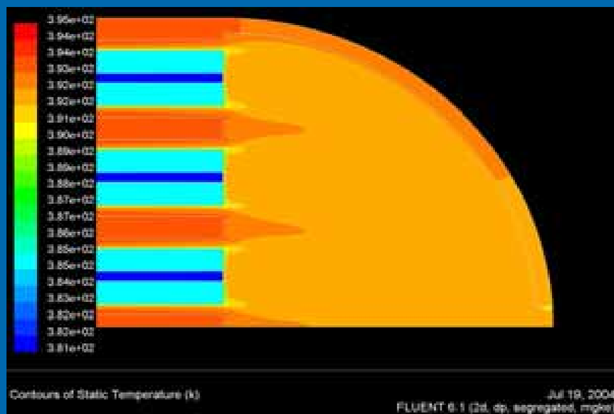
$$\left|Q_{loss}\right| = \left|Q_h\right| - \left|Q_c\right|$$



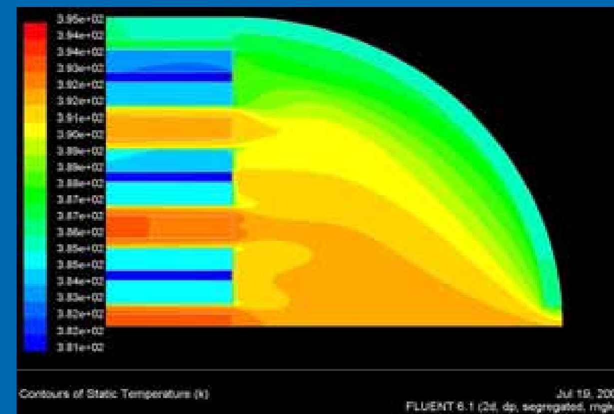
Heat Loss Estimation (2)

Effect on the outlet temperatures:

3) From 2D FLUENT CFD calculations (with(2)/without(1) heat loss)

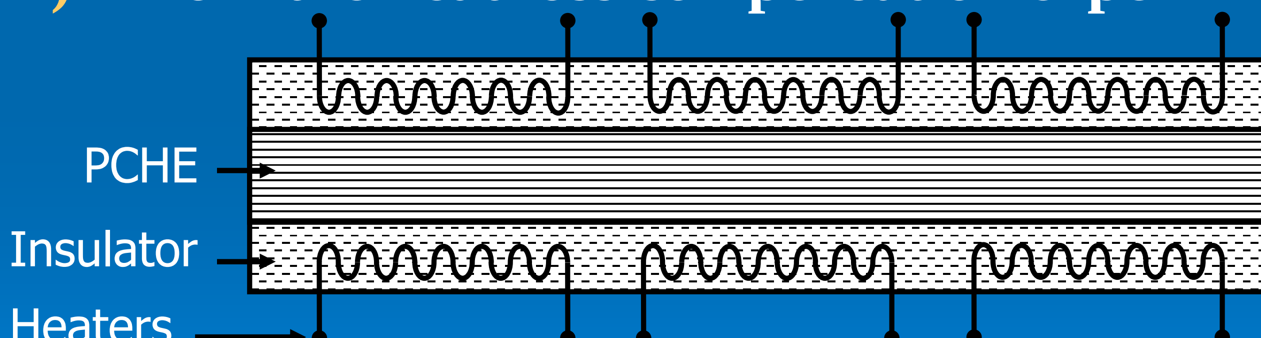


(1)



(2)

4) From the heat loss compensation experiments

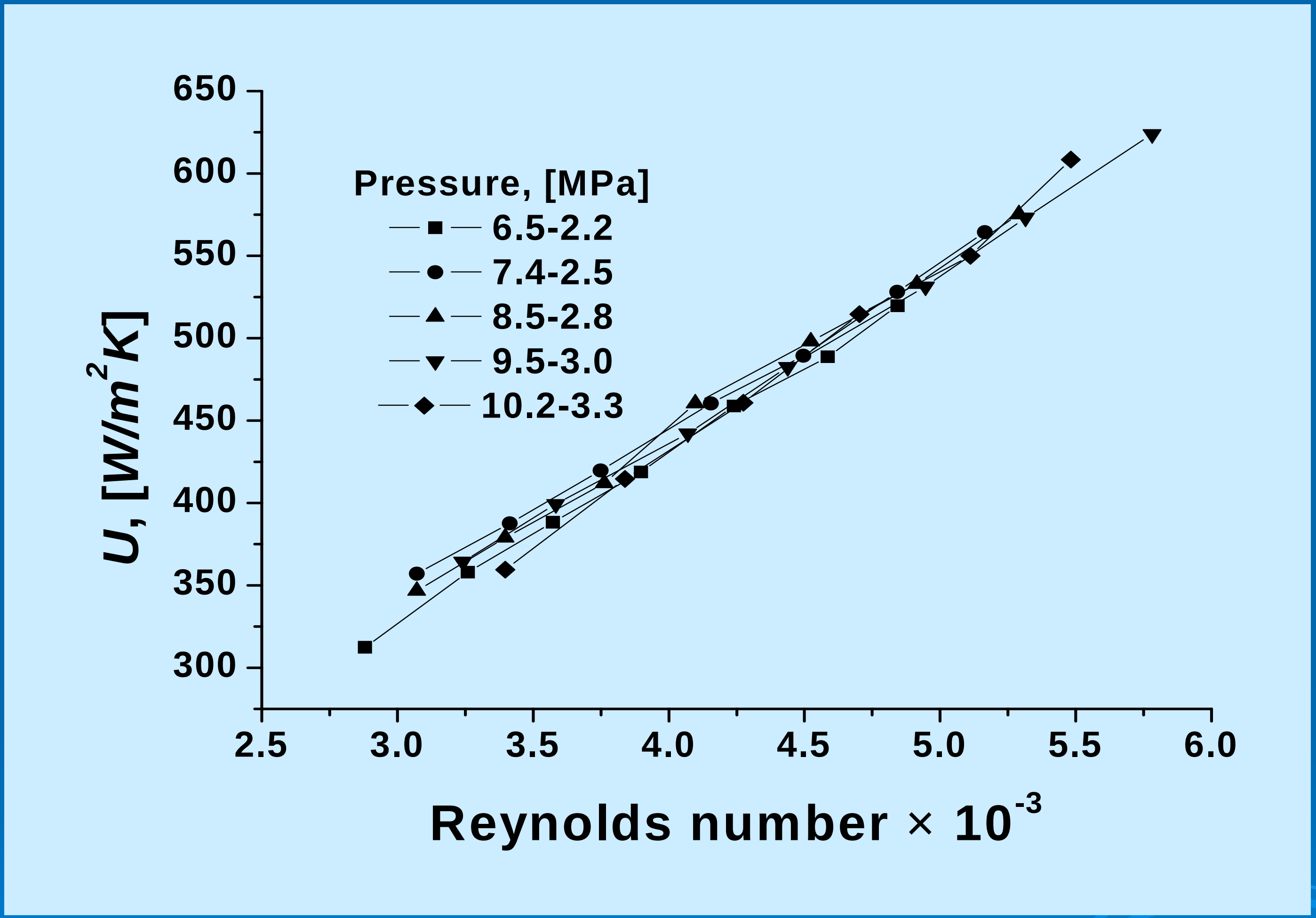


$$T^{k}_{PCHE-surf} = T^{k}_{near-heater-surf}$$

$$Q_{loss} \approx 0$$

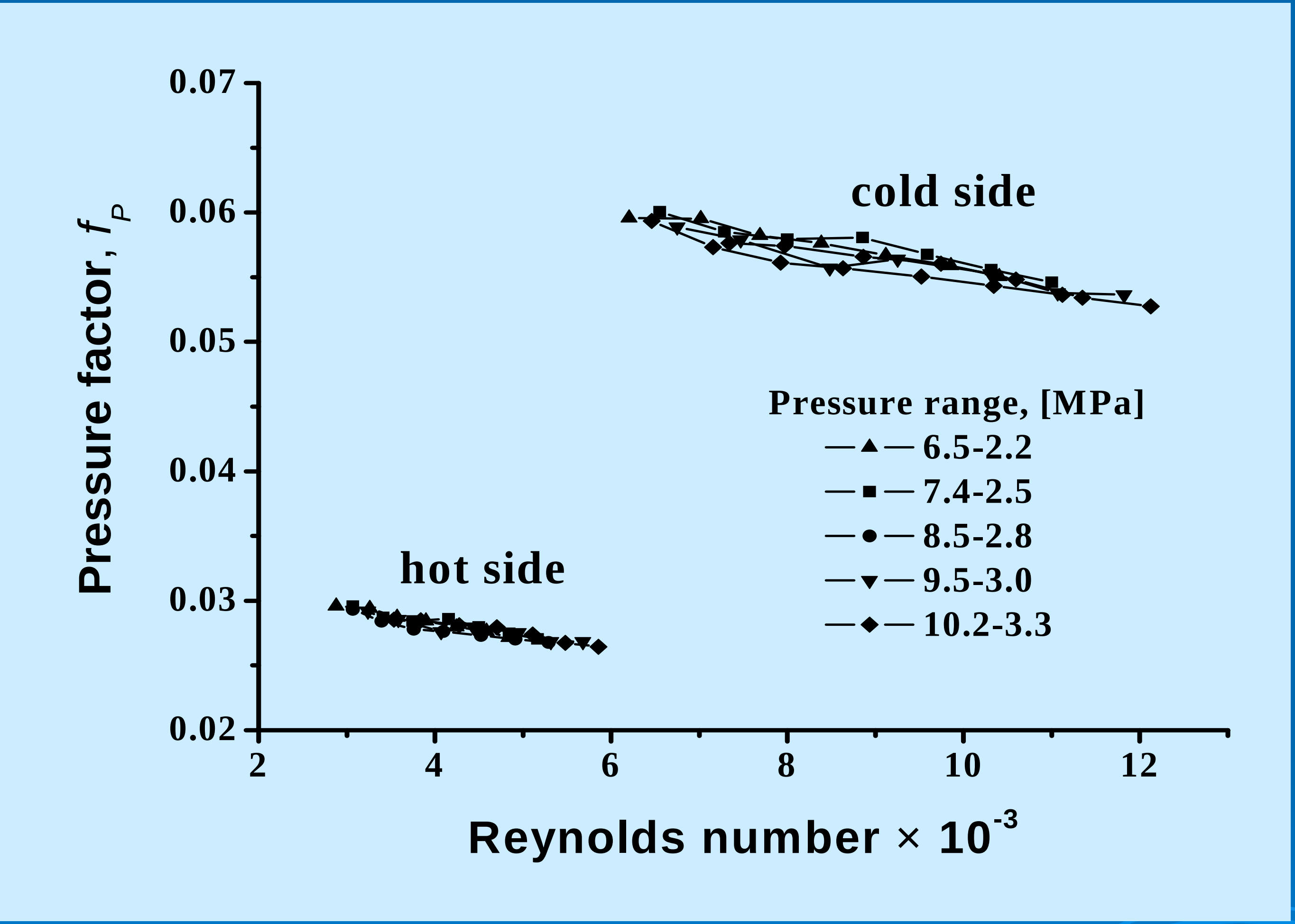
$$\Delta T_{hot,out}: \quad W_{hot} \times \int_{T_{hot,out}}^{T_{hot,out}+\Delta T_{hot,out}} Cp(P(T),T)dT = -0.35Q'_{loss}; \quad \Delta T_{cold,out}: \quad W_{cold} \times \int_{T_{cold,out}}^{T_{cold,out}+\Delta T_{cold,out}} Cp(P(T),T)dT = -0.65Q'_{loss}$$

Overall heat transfer coefficient, U



$$U = (18.6 \pm 6.8) + (0.105 \pm 0.002) \times \mathrm{Re}, \qquad 2 \times 10^3 < \mathrm{Re} < 6 \times 10^3$$

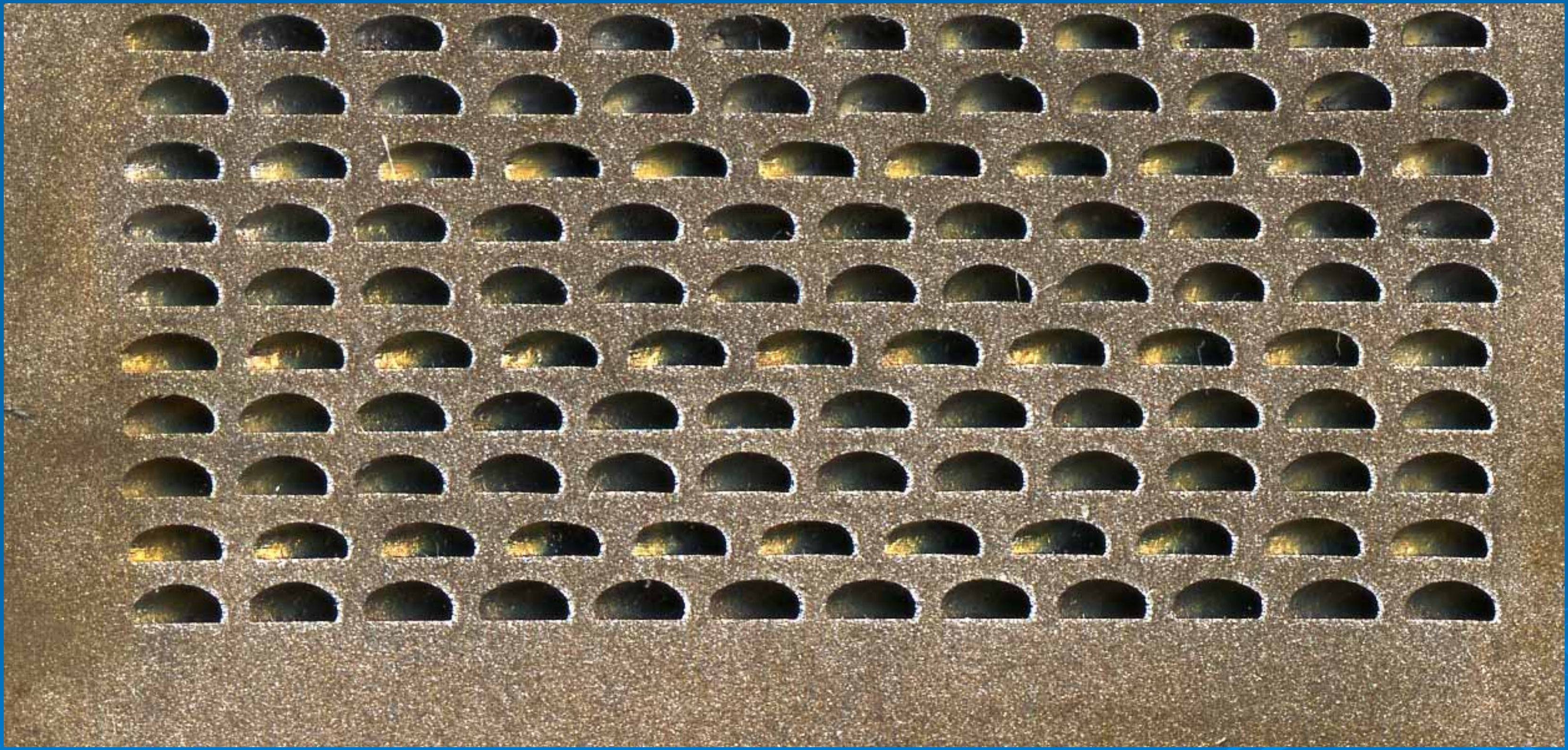
Pressure factor, f_P



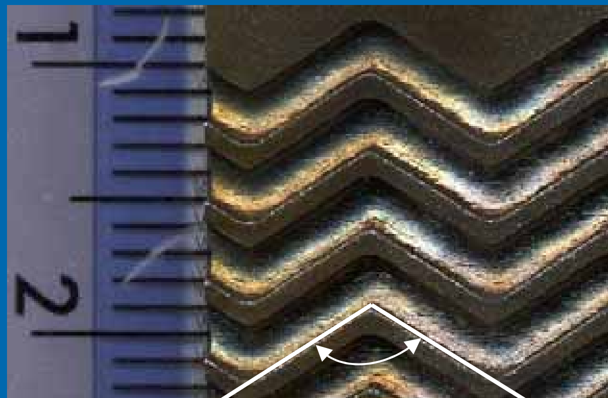
$$f_{P,hot} = (0.032 \pm 0.002) - (1.01 \times 10^{-6} \pm 6 \times 10^{-8}) \times Re, \quad 2 \times 10^3 \le Re \le 6 \times 10^3$$

$$f_{P,cold} = (0.066 \pm 0.001) - (1.11 \times 10^{-6} \pm 7 \times 10^{-8}) \times Re, \quad 6 \times 10^3 \le Re \le 12 \times 10^3$$

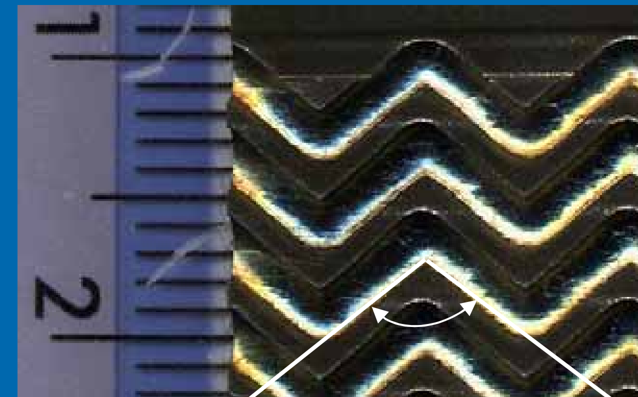
PCHE cross-section



Head loss in PCHE



115°



100°

$$\Delta p = \rho g \Delta H = \sum_m \rho_m K_b \frac{U_m^2}{2} + \sum_m \rho_m 0.316\,\mathrm{Re}^{-0.25} \frac{L_a}{md} \frac{U_m^2}{2}$$

loss in elbows + loss in a straight pipe

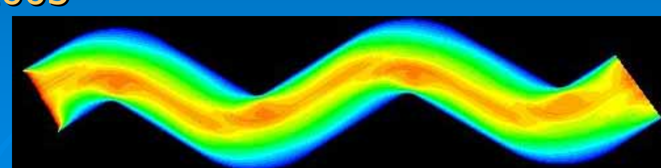
I. $K_b = K_1 * K_2 * K_3$: $\left|\frac{\Delta p_{calc} - \Delta p_{\exp}}{\Delta p_{\exp}}\right| = 14 - 37\%$

from Hydraulic Engineering, A. Lencastre, 1987

II. $K_b = 0.946 \sin^2\left(\frac{\theta}{2}\right) + 2.047 \sin^4\left(\frac{\theta}{2}\right)$: $\left|\frac{\Delta p_{calc} - \Delta p_{\exp}}{\Delta p_{\exp}}\right| = 6 - 32\%$

from JSME Textbook, 2003

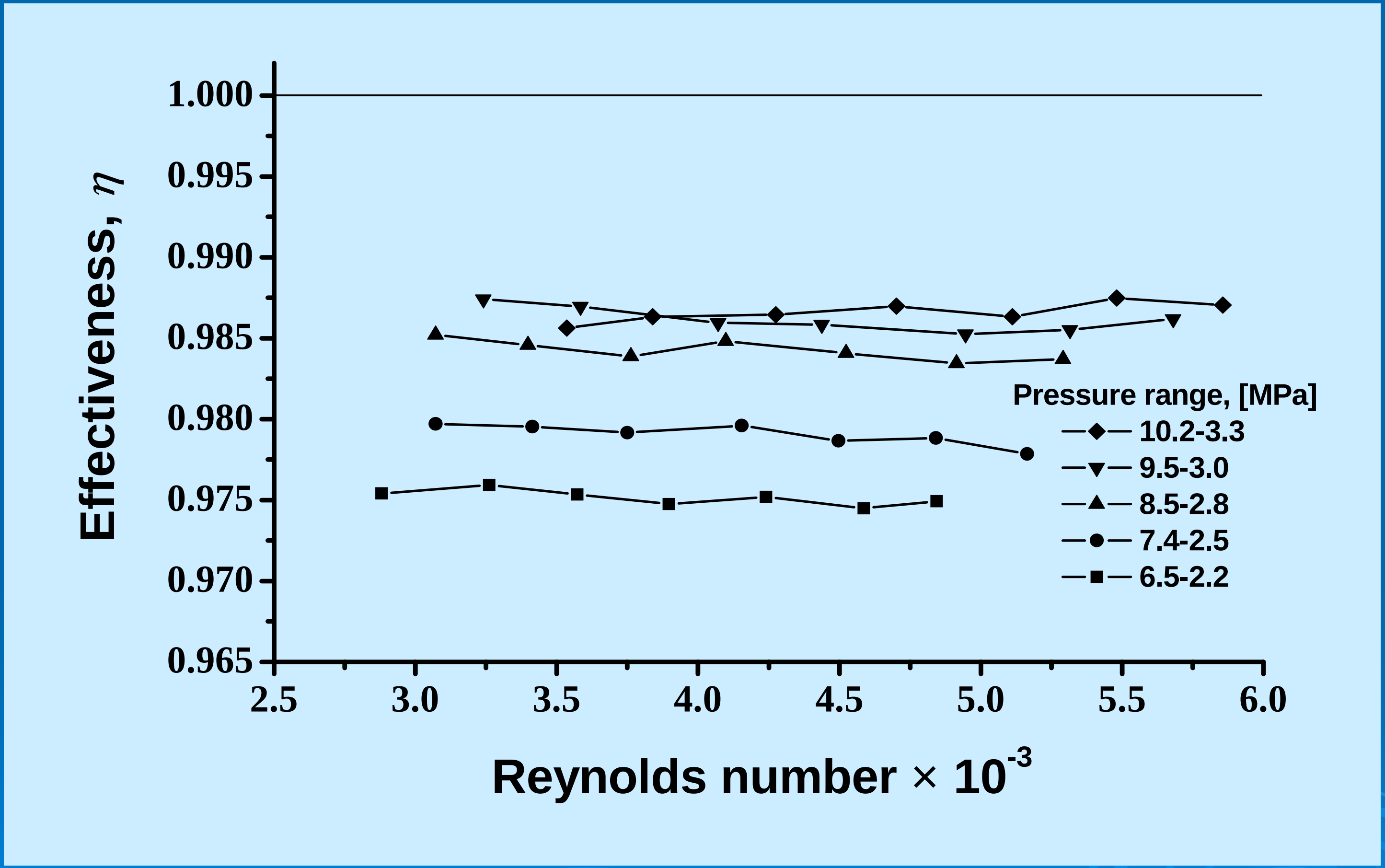
III. CFD FLUENT



: N/A yet

PCHE's Effectiveness

Effectiveness:
$$\eta = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{C_c\left(T_{c,o} - T_{c,i}\right)}{C_{min}\left(T_{h,i} - T_{c,i}\right)}$$

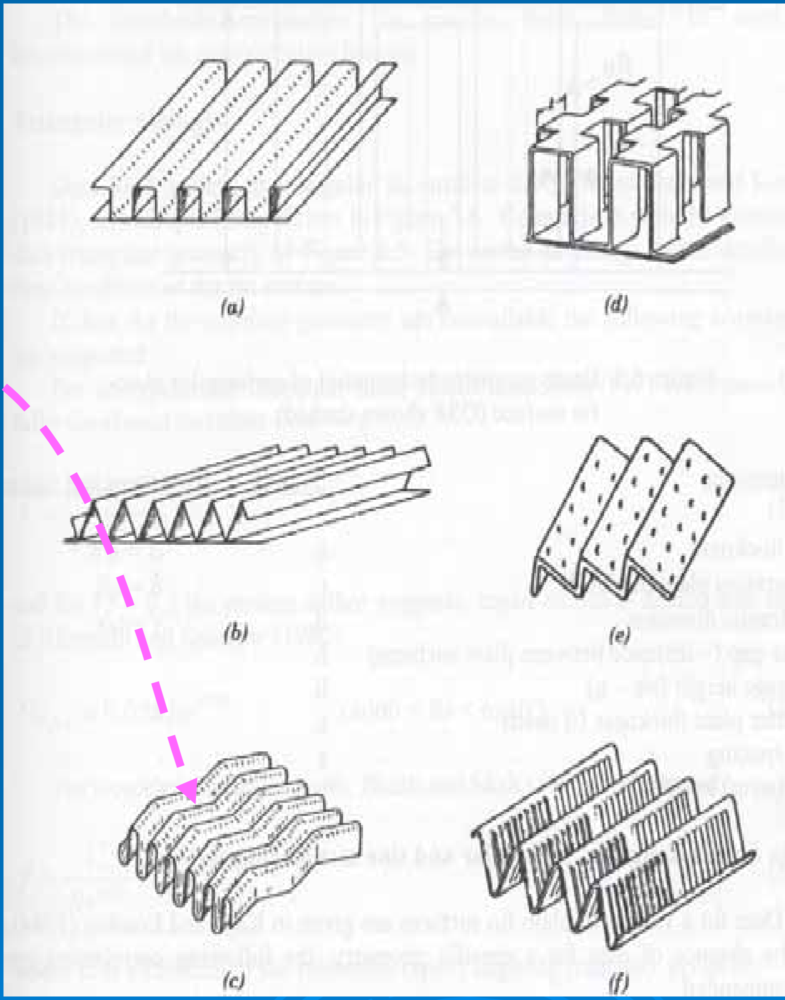


PCHE's effectiveness reaches value up to 98.7%.

1% of recuperator effectiveness ➔ the gas turbine cycle efficiency 0.6%

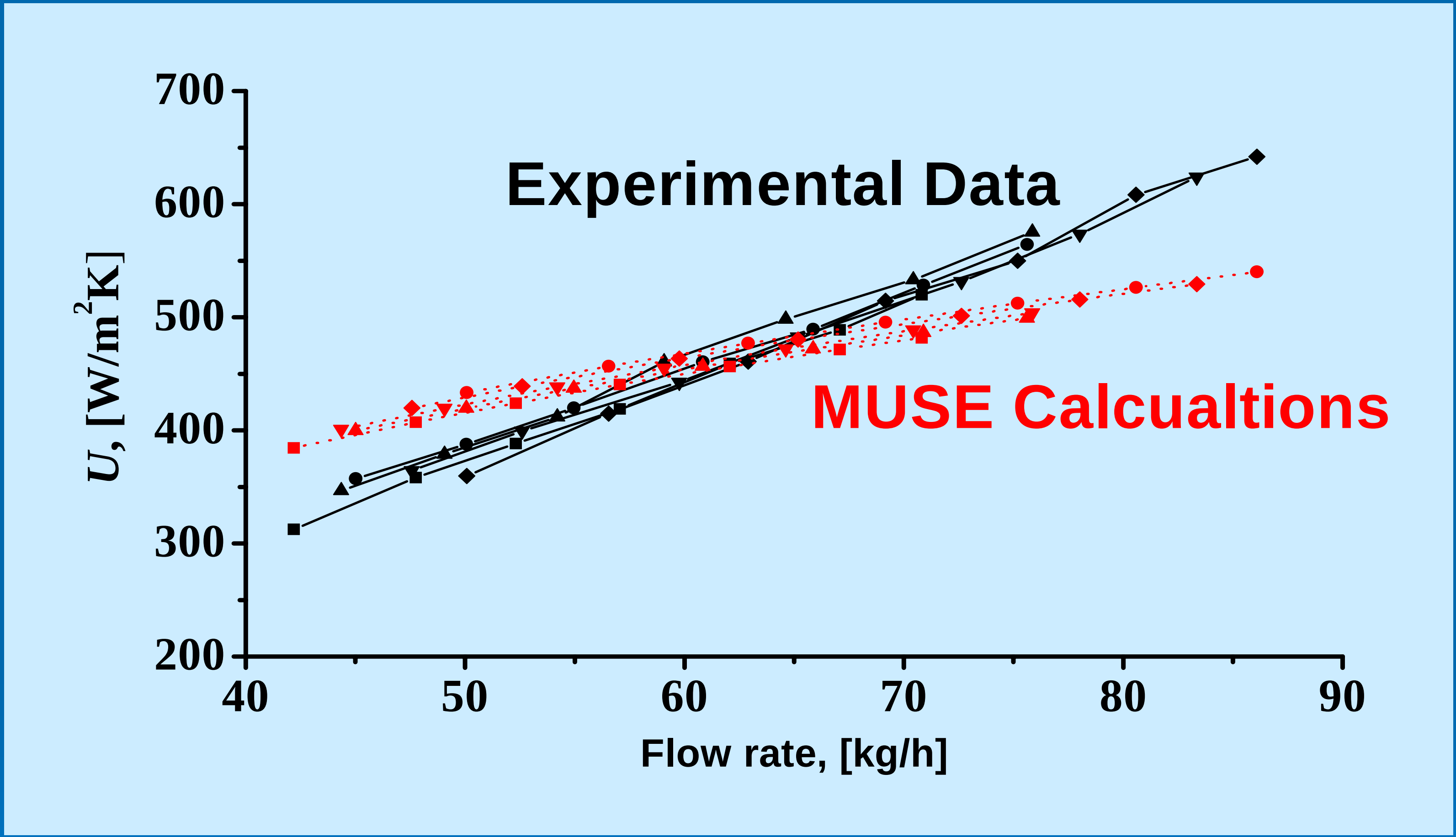
MUSE Code Simulation

- Developed for plate-fin heat exchanger,
- Use Wavy fin plate heat exchanger model,
- This model is the most similar model to our tested PCHE.



Various plate-fin models

Experimental data & MUSE Calculations



The different slopes may be due to:

- **Difference of PCHE from wavy fin model,**
- **Neglect of cross flow in the distributor sections.**

Conclusions

- The overall heat transfer coefficient and pressure loss factor of PCHE were investigated both experimentally and numerically; the empirical correlations are proposed.

- The method to take into account the heat loss for overall heat transfer coefficient estimations has been established.

- The overall heat transfer coefficient varies from 300 to 650 W/m^2K while the heat transfer effectiveness reaches up to 98.7 %.

- PCHE might be judged as a promising compact heat exchanger for the high efficiency recuperator.

- The experimental data are currently used for CFD FLUENT code verification and developing the new heat exchanger type.