Investigation and optimization of the continuous and discrete heat exchangers in the mK dilution refrigerator for cooling superconducting quantum chips

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Introduction

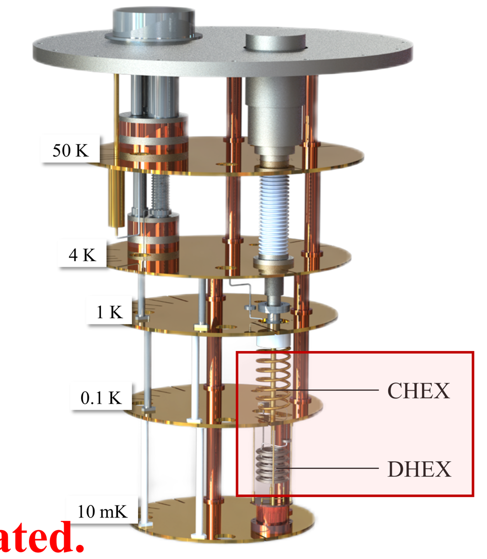
Superconducting quantum computing demand:

- Ultra-low temperature: 10~100 mK
- Low vibration
- Low electromagnetic interference

❖ Dilution refrigerator (DR) has become an indispensable technology to provide cryogenic environment for the quantum chips.

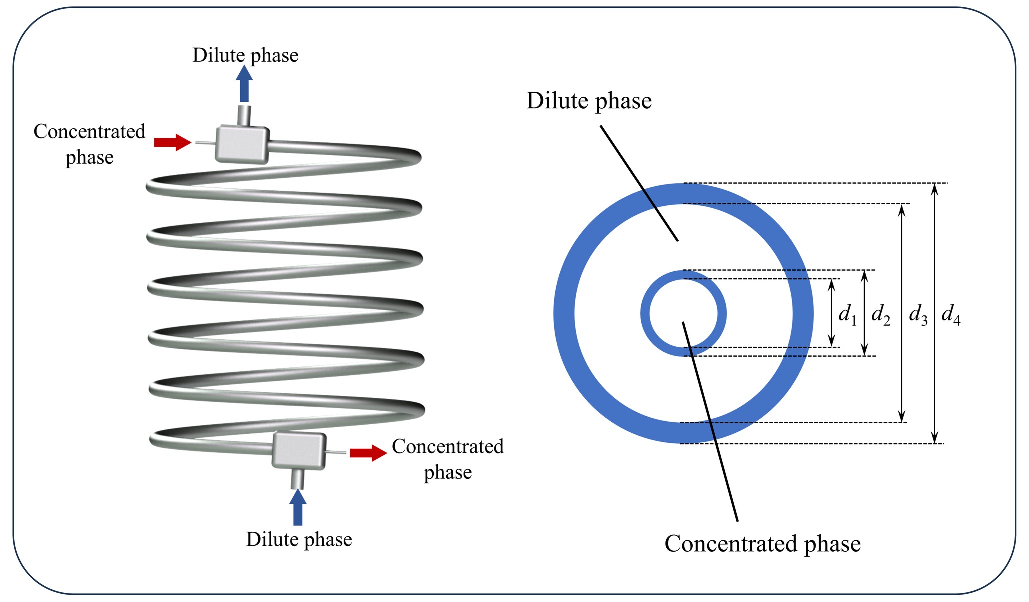
❖ Two types of heat exchangers (HEXs) plays crucial role in the DR, including the continous heat exchanger (CHEX) and the discrete heat exchanger (DHEX).

❖ The flow and heat transfer characteristics is related to working conditions and dimensional parameters of heat exchangers



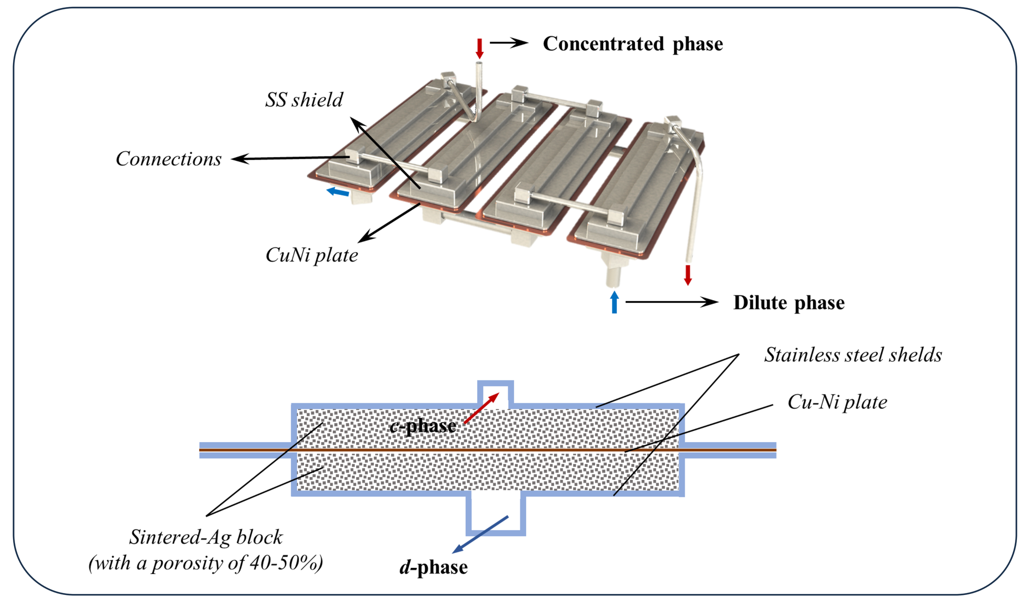
- **Numerical model of two types of heat exchangers are established.**
- **Effects of dimensions, Kapitza resistance and viscous heating are investigated.**
- **Both heat exchangers are optimized.**

Physical Models



(1) Outlook and internal design of a CHEX

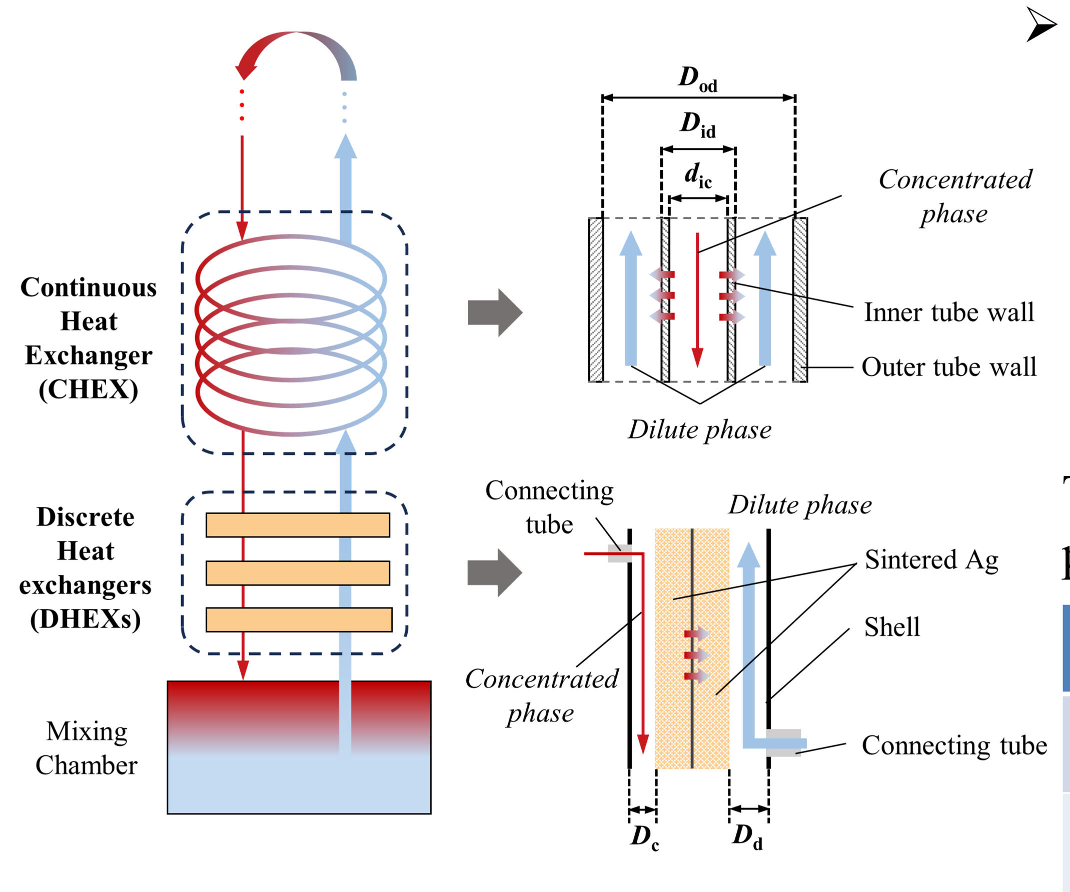
- The concentrated phase flows into the inner tube while the dilute phase flows into the annular space.
- The spiral inner tube is used to increase the heat exchange area and suppress heat transfer deterioration due to evaporation.
- The material of both inner and outer tube is *CuNi* in order to reduce axial heat transfer and enhance radial heat conduction simultaneously.



(2) Outlook and inner components of DHEXs

- Each DHEX consists of a thin *CuNi* plate, two sintered Ag blocks and stainless steel shelds.
- The concentrated phase flows in the upper channel while the dilute phase in the lager channel which is 4 times the cross-sectional area of the upper one.
- The Ag block can increase the heat transfer area by several orders of magnitude to compensate for Kapitza resistance below 100mK.

Theoretical Analysis and Numerical Modeling



Two types of heat exchangers in the DR below 1 K

- According to the conservation of energy, the coupled heat transfer governing equation of the heat exchangers below 1K can be summarized as:

$$X\frac{d}{dx}\left(\frac{dT_i}{dx}\right)+Y\frac{128\dot{n}^2}{\pi}+Z\left(T_c^4-T_d^4\right)=\dot{n}C_i\frac{dT_i}{dx}$$

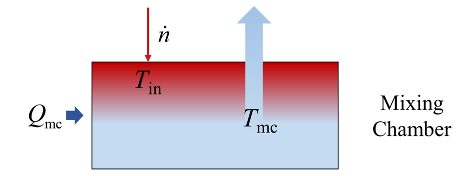
axial heat conduction — *viscous heating* — *lateral interface heat transfer*

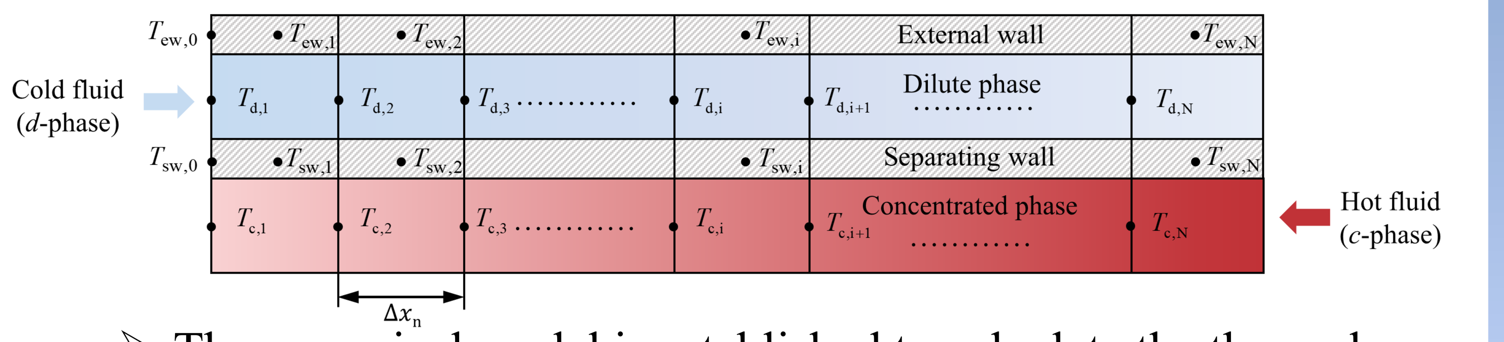
The coefficients of the equation for the concentrated and dilute phase in both heat exchangers are given in the table below.

	CHEX (c-phase)	CHEX(d-phase)	DHEX(c-phase)	DHEX(d-phase)
X	$\frac{\pi d_{ic}^2}{4}k_c$	$\frac{\pi(D_{od}^2-D_{id}^2)}{4}k_d$	$\left(\varphi A_{sintered\text{-}Ag}+\frac{\pi D_c^2}{4}\right)k_c$	$\left(\varphi A_{sintered\text{-}Ag}+\frac{\pi D_d^2}{4}\right)k_d$
Y	$\frac{\eta_c V_c^2}{d_{ic}^4}$	$\frac{\eta_d V_d^2}{(D_{od}-D_{id})^2(D_{od}^2-D_{id}^2)}$	$\frac{\eta_c V_c^2}{D_c^4}$	$\frac{\eta_d V_d^2}{D_d^4}$
Z	$\frac{A_{ic}}{4R_{k,c}}$	$\frac{A_{od}}{4R_{k,d}}$	$\frac{\gamma A_{sintered-Ag}}{4R_{k,c}}$	$\frac{\gamma A_{sintered-Ag}}{4R_{k,d}}$

- According to the enthalpy balance in the mixing chamber, the cooling capacity of the DR is:

$$Q_{mc}=\dot{n}(H_d(x_s,T_{mc})-H_3(T_{in}))$$

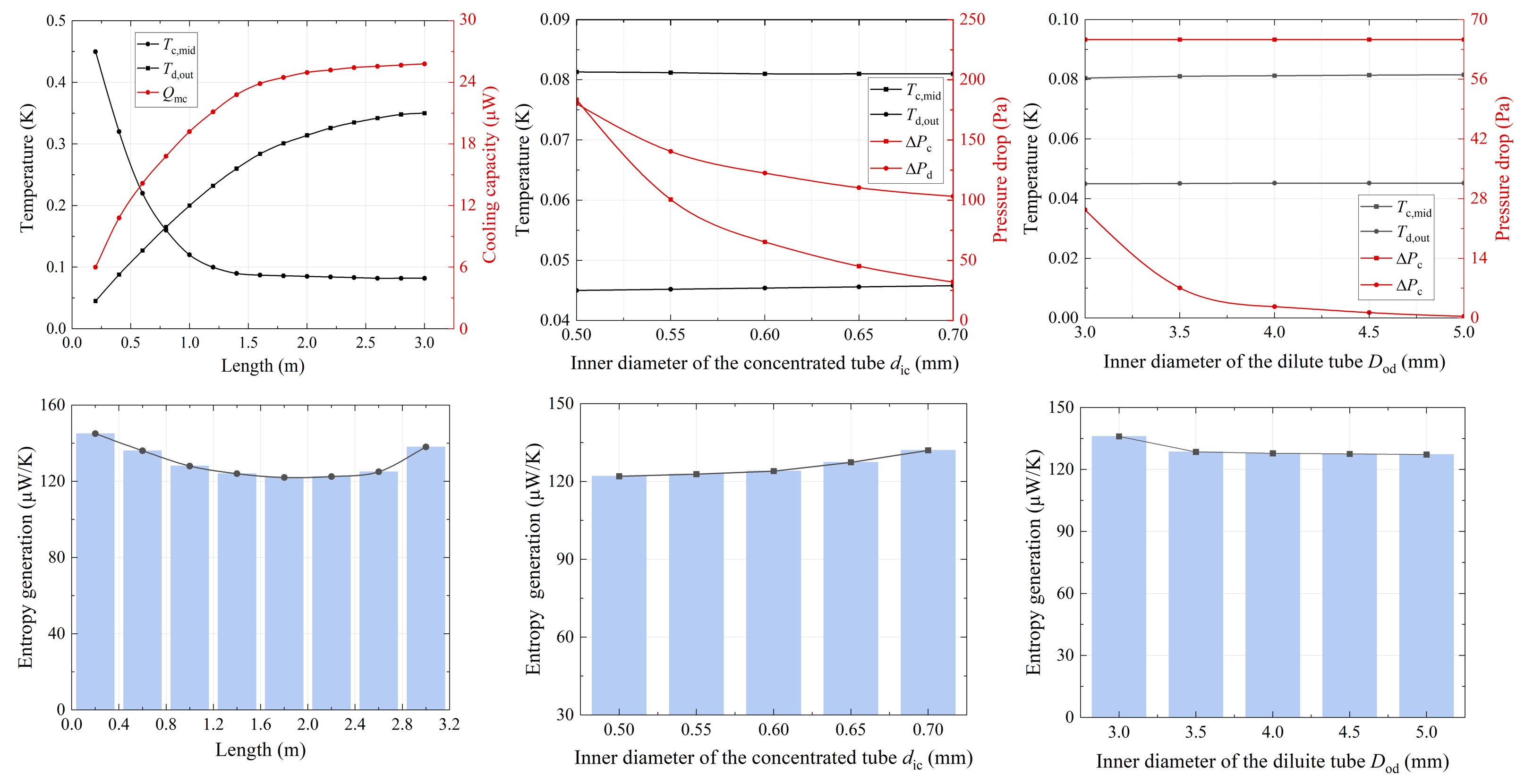




- The numerical model is established to calculate the thermal performance based on the finite volume method.
- The heat exchangers are regarded as a one-dimensional model, and divided into N segments along the length.
- The boundary working conditions are given by:

$$T_{c,N+1}=T_s=0.7\ \text{K}\qquad T_{d,1}=T_{mc}\qquad T_{c,1}=T_{in}\qquad \dot{n}=200\ \mu\text{mol/s}$$

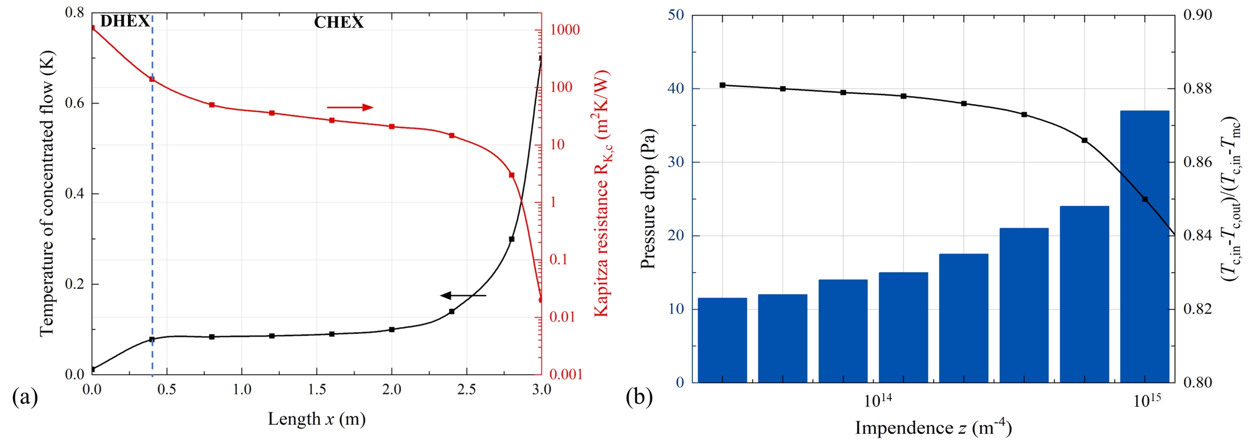
Discussion and Optimization



Relationship between thermal and flow parameters and dimensions in the CHEX

- The optimal dimensions: ***L*=2.6m *d*$_{ic}$=0.6mm *D*$_{od}$=4mm.**

- With the optimal dimensions, taking the CHEX and DHEXs as a whole, the effects of Kapitza resistance and viscous heating are shown below.
- When the concentrated side is cooled below 0.1 K, the Kapitza thermal resistance becomes extremely large.
- Therefore, the impendence of HEXs should be confined below $2\times10^{14}\ \text{m}^{-4}$ to avoid the degradation of heat transfer characteristics caused by pressure drop.



The effects of Kapitza resistance and viscous heating

Conclusions

◆ The numerical model of heat exchangers in the dilution refrigerator is established to investigate its cooling performance.

◆ The optimal dimensions of the continuous heat exchanger should achieve a trade-off between cooling performance and irreversible loss.

◆ For the discrete heat exchanger, the heat transfer and flow characteristics are strongly influenced by the Kapitza thermal resistance and impedance below 1 K.

◆ With the optimized heat exchangers, the cooling capacity of the dilution refrigerator can be improved by 30% in this study to accommodate more qubits for the booming superconducting quantum computers.