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Study on a cascade pulse tube cooler with energy recovery

—*New method for approaching Carnot*

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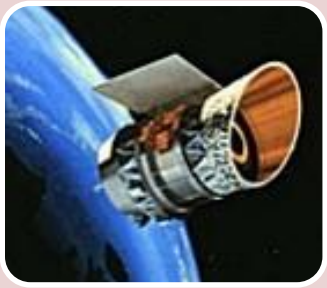
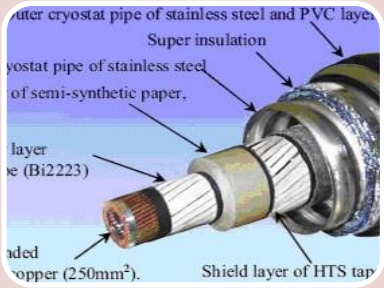
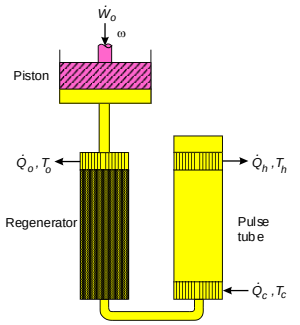
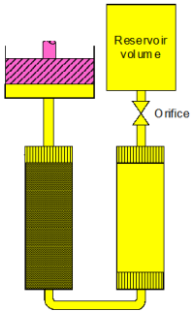
Motivation



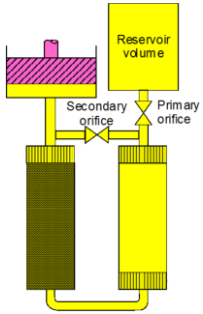




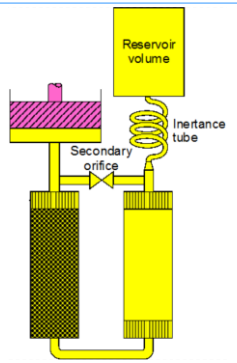
Basic type



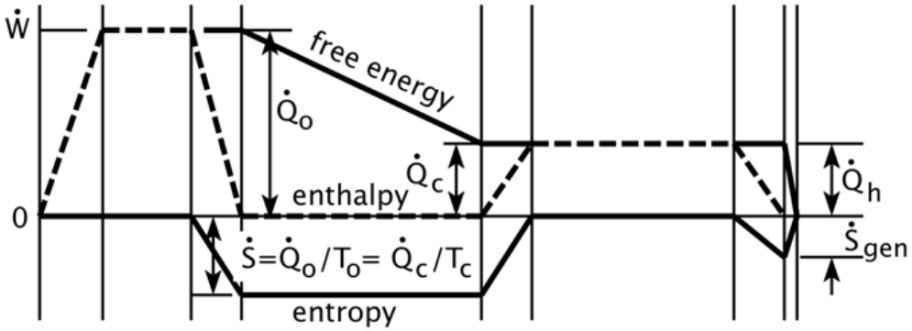
Orifice type



Double inlet

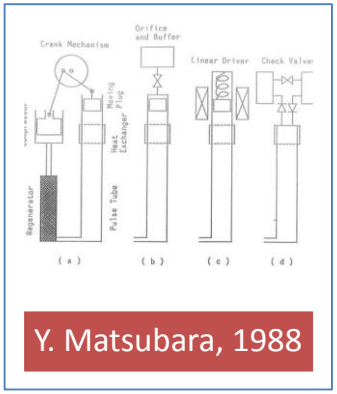


Inertance tube

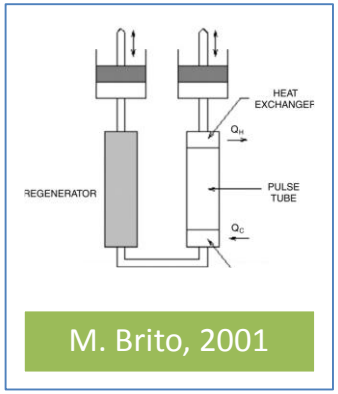


$$\eta = \frac{T_c}{T_h} < \eta_c = \frac{T_c}{T_h - T_c}$$

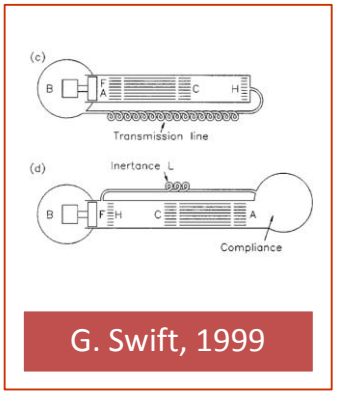
PTCs with work recovery



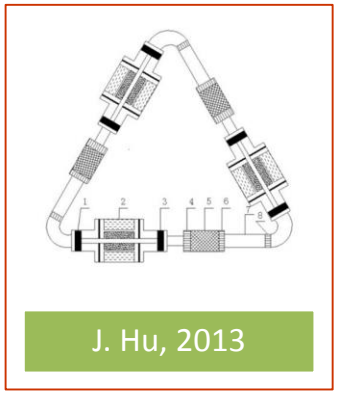
Y. Matsubara, 1988



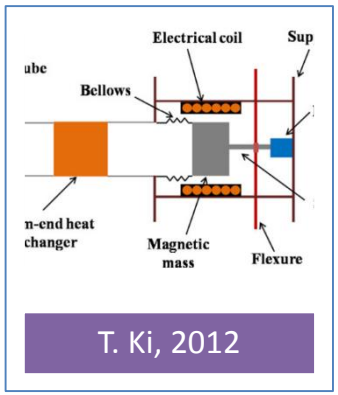
M. Brito, 2001



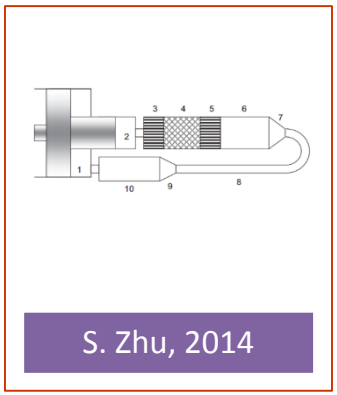
G. Swift, 1999



J. Hu, 2013



T. Ki, 2012



S. Zhu, 2014

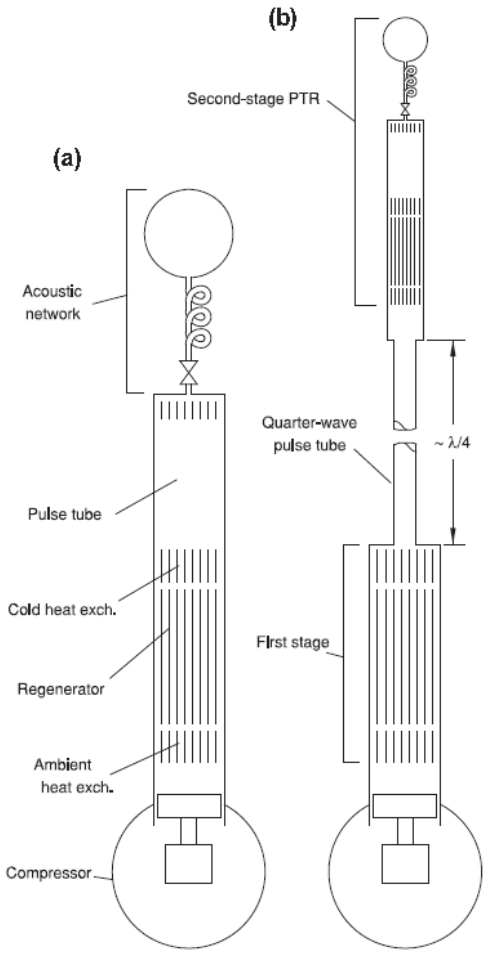
1

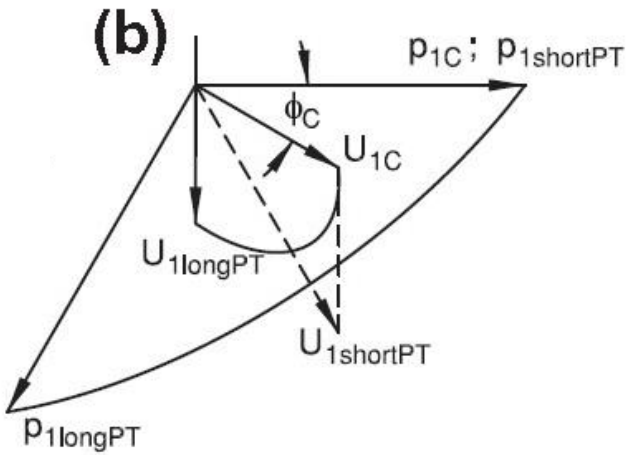
- By introducing moving parts at the warm end of the pulse tube
- Introduce vibration, lower the reliability

2

- Through loop configurations
- Cause streaming that deteriorates the cooling performance

PTCs with work recovery





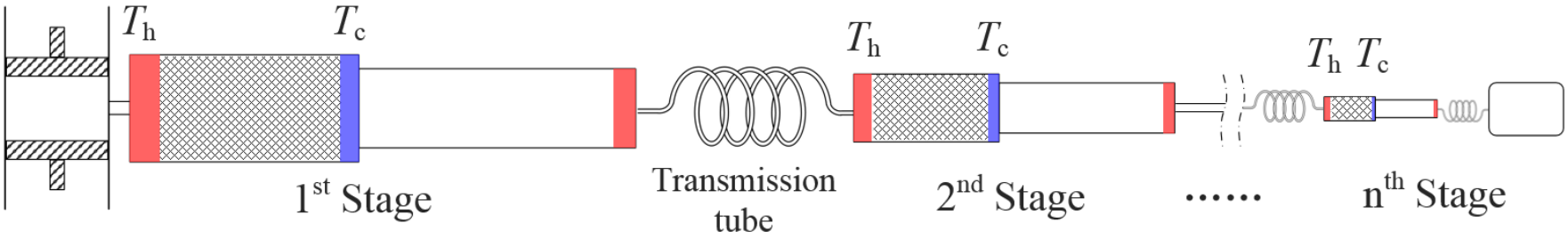
3

- Neither moving parts nor streaming brought in

G. Swift 2011

Contents

A cascade PTC



$$COP = \frac{T_c}{T_h} \qquad \left(\frac{T_c}{T_h}\right)^2 \qquad \left(\frac{T_c}{T_h}\right)^n$$

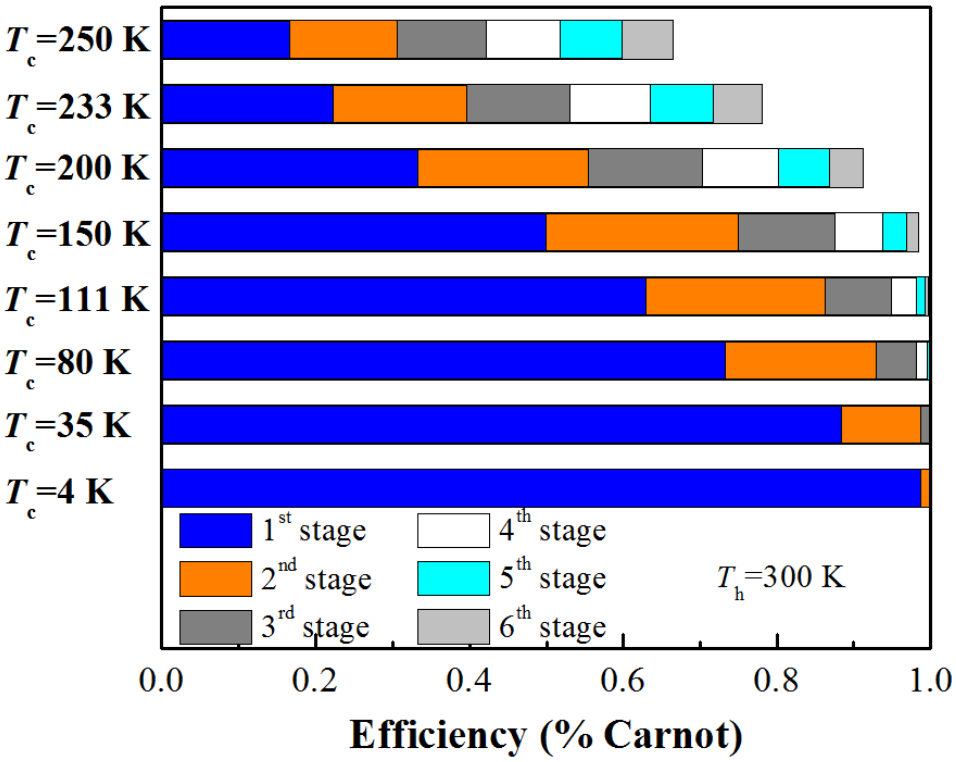
$$Q_{c1} = E_1 \frac{T_c}{T_h} \qquad E_2 = Q_{c1} = E_1 \frac{T_c}{T_h} \qquad Q_{c2} = E_2 \frac{T_c}{T_h} = E_1 \left(\frac{T_c}{T_h}\right)^2 \qquad Q_{cn} = E_{n-1} \frac{T_c}{T_h} = E_1 \left(\frac{T_c}{T_h}\right)^n$$

$$COP_n = \frac{Q_{c1} + Q_{c2} + \cdots + Q_{cn}}{E_1} = \frac{T_c}{T_h} + \left(\frac{T_c}{T_h}\right)^2 + \left(\frac{T_c}{T_h}\right)^3 + \cdots + \left(\frac{T_c}{T_h}\right)^n = \frac{T_c}{T_h - T_c}\left[1 - \left(\frac{T_c}{T_h}\right)^n\right]$$

$$COP_{n\to\infty} = \frac{T_c}{T_h - T_c}$$

A cascade PTC

$$COP_n = \frac{Q_{c1} + Q_{c2} + \cdots + Q_{cn}}{E_1} = \frac{T_c}{T_h} + \left(\frac{T_c}{T_h}\right)^2 + \left(\frac{T_c}{T_h}\right)^3 + \cdots + \left(\frac{T_c}{T_h}\right)^n = \frac{T_c}{T_h - T_c}\left[1 - \left(\frac{T_c}{T_h}\right)^n\right]$$



- In lower temperature region, the single stage PTC can almost get to the Carnot efficiency
- As the cooling temperature goes up, the benefit of cascading stages becomes more and more noticeable

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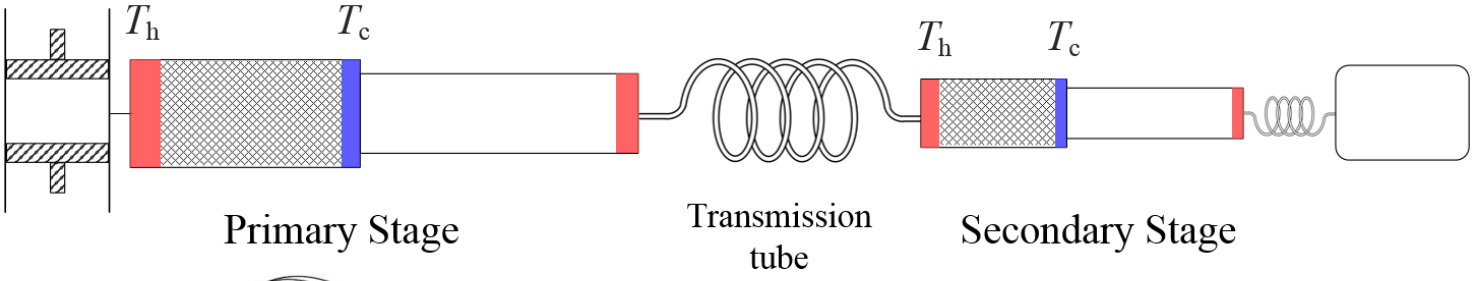
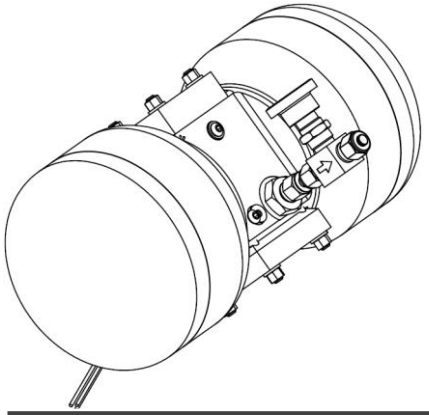
Practical Considerations



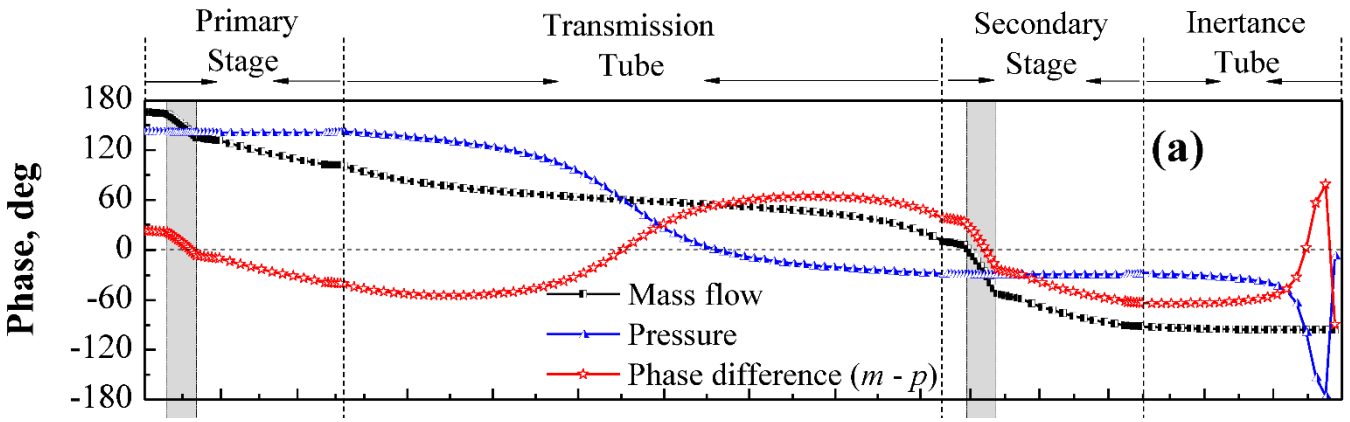


- ✓ High cooling temperature
- ✓ High cooling power

CFIC 2s132	
f / Hz	60
p_0 / MPa	2.5
W_e / W	500

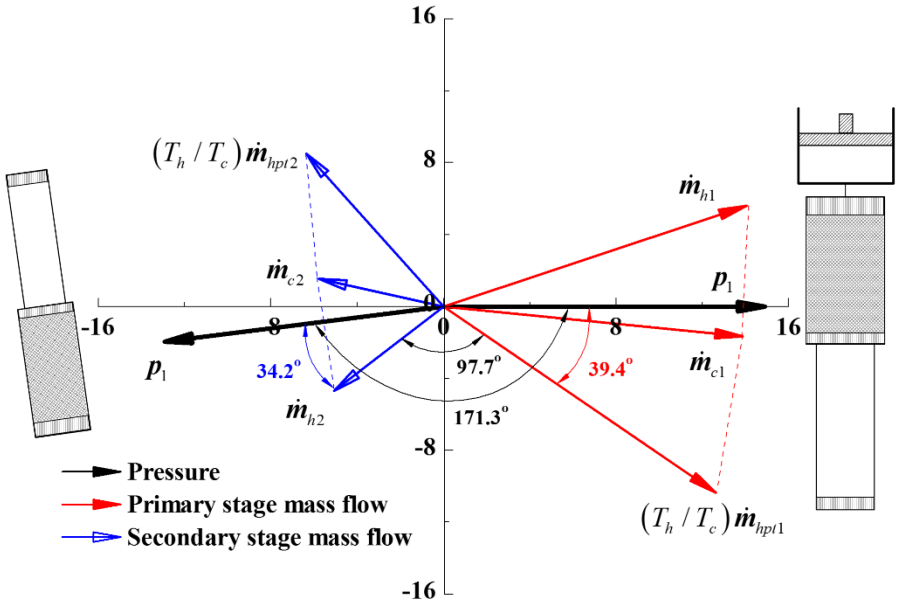
Design goal	
T_c / K	233(−40℃)
Q_c / W	200

Flow distributions



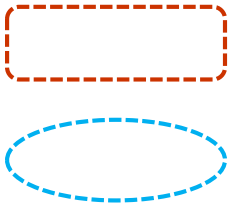
θ

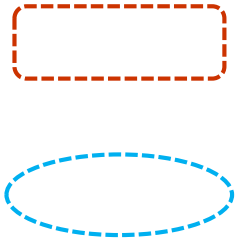
- The negative phase at the outlet of the primary PTC is turned positive at the inlet of the secondary PTC



Flow distributions

m	• first increases and then decreases along the transmission tube • two regenerators are located near the two antinodes of the mass flow wave





p	• decreases progressively in both PTCs • decreases first and then increases to a large extent along the transmission tube • two regenerators are located near the two peaks of the pressure wave

Flow distributions

PV	• 204.7 W PV work is recovered • 79 W is consumed in this long tube • 125.7 W arrives the secondary PTC • the cascade pulse tube cooler is still far from ‘ideal’ due to some inherent losses
H	• enthalpy flow in the two PTCs are similar as that of a normal single-stage PTC

Calculation results

	Single stage PTC	Cascade PTC		
		Primary stage	Secondary stage	cascade
f / Hz		60		
P_0 / MPa		2.5		
W_e / W		500		
PV work input / W	389.9	379.1	125.7	379.1
Pressure ratio at the hot end	1.214	1.168	1.146	1.168
Pressure ratio at the cold end	1.204	1.155	1.139	–
Cooling power at 233 K / W	196.3	184.5	65.1	***249.6***
COP	0.3926	0.369	–	0.4992
Percent of Carnot / %	11.29	10.61	–	14.35

✓ **Cascade PTC can bring an extra cooling efficiency of 27%**

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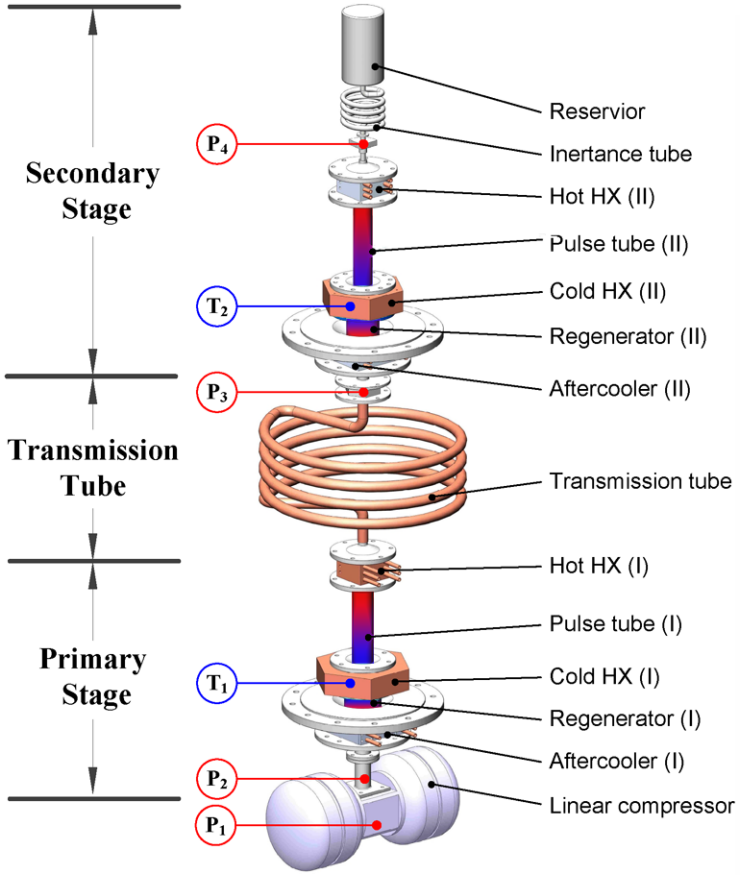
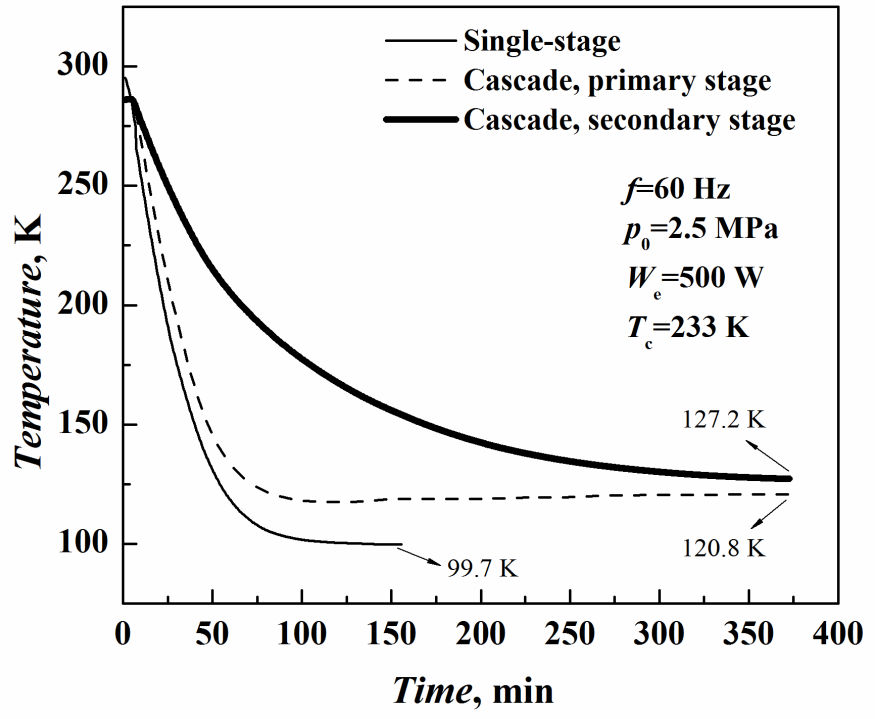
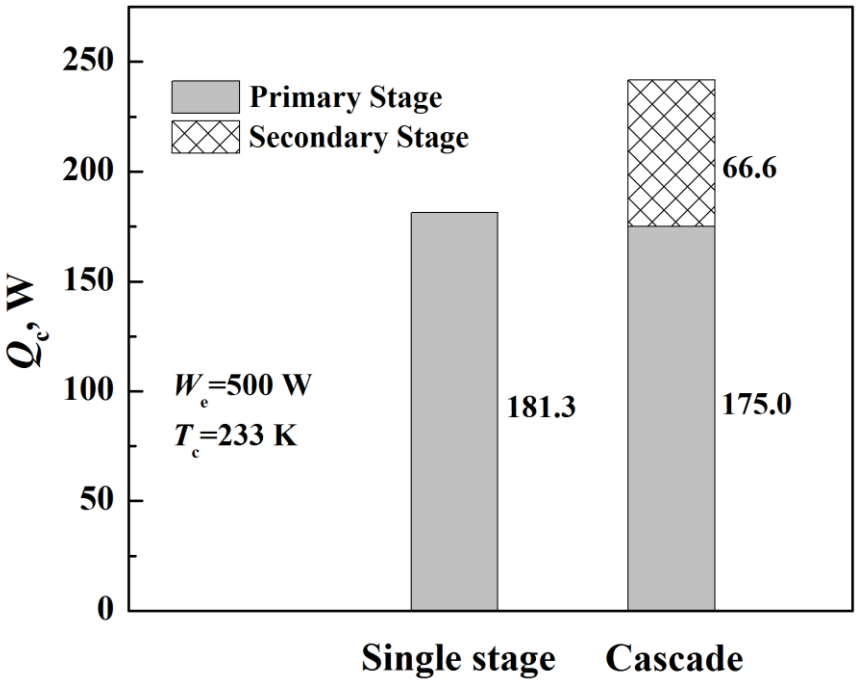
Experimental setup



	Parts Name	Dimension
Primary Stage	REG	53.7 mm i.d., 37.7 mm long
	PT	30.5 mm i.d., 134.3 mm long
	IT	8 mm i.d., 2.67 m long
	RES	450 cm^3
Transmission tube	14.2 mm i.d., *7 m long*	
Secondary Stage	REG	47.6 mm i.d., 48 mm long
	PT	27 mm i.d., 150 mm long
	IT	6 mm i.d., 1.4 m long
	RES	1000 cm^3

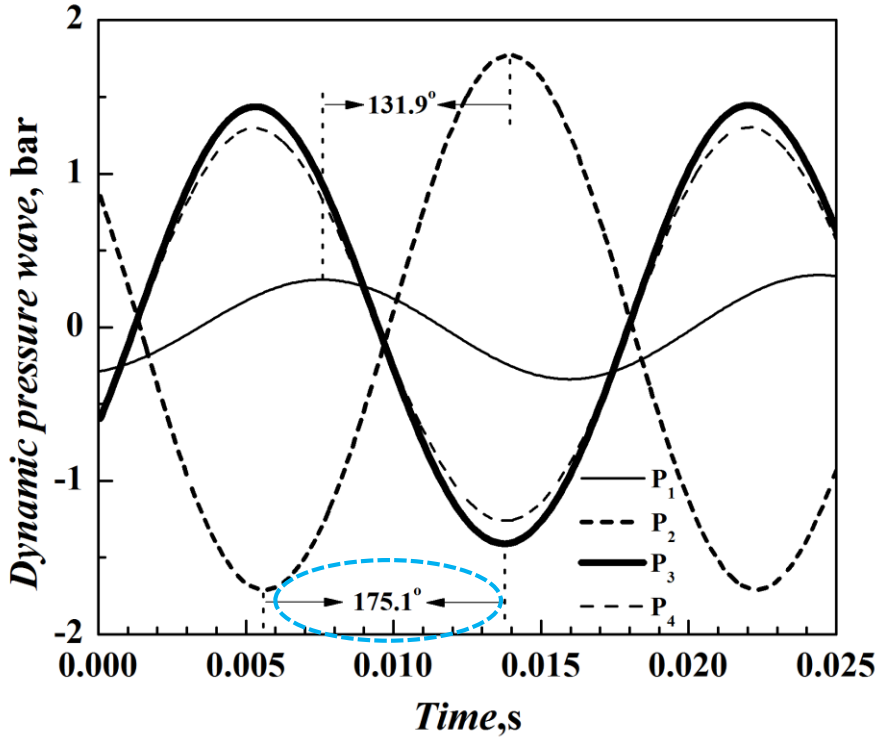
Experimental results

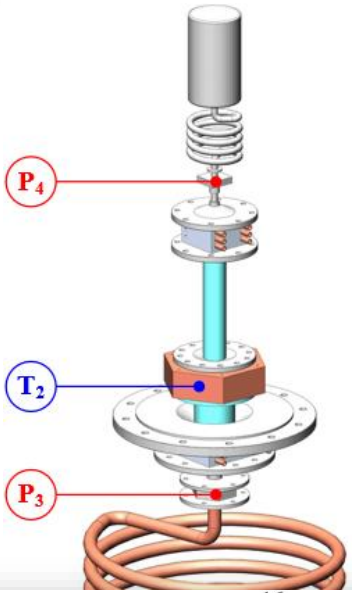


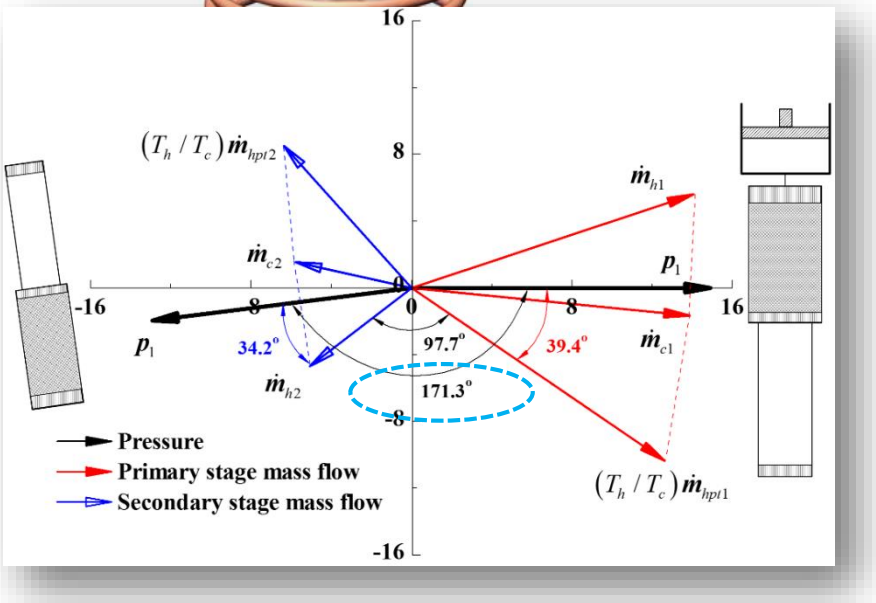


	Single stage PTC	Cascade PTC		
		Primary stage	Secondary stage	cascade
Cooling power at 233 K / W	196.3	184.5	65.1	249.6

Experimental results







Contents

Conclusions

- ✓ A multi-stage cascade PTC is proposed, theoretical analysis shows that the more stages it has, the closer its efficiency will approach to the Carnot efficiency
- ✓ A two-stage cascade PTC is designed, simulation results show that 125.7 W of the 204.7 W PV work at the warm end of the pulse tube could be recovered for driving the secondary PTC
- ✓ Experimental results accord well with calculated results, with 500 W electric power input, the cascade PTC obtains a total cooling power of 241.6 W at 233 K, the cooling efficiency is increased by 33%

Thanks for your attention!