



Cryogenic Engineering Conference & International Cryogenic Materials Conference

Tucson, Arizona, June 28 – July 2, 2015
Presentation ID: C2OrC Paper ID: 173



Experimental investigation on a pulsating heat pipe with hydrogen



**Haoren DENG, Yumeng LIU, Renfei MA,
Dongyang HAN, Zhihua GAN**
Zhejiang University

John Pfotenhauer*

University of Wisconsin-Madison

June 30, 2015

Contents

1. Introduction

2. Experimental Setup

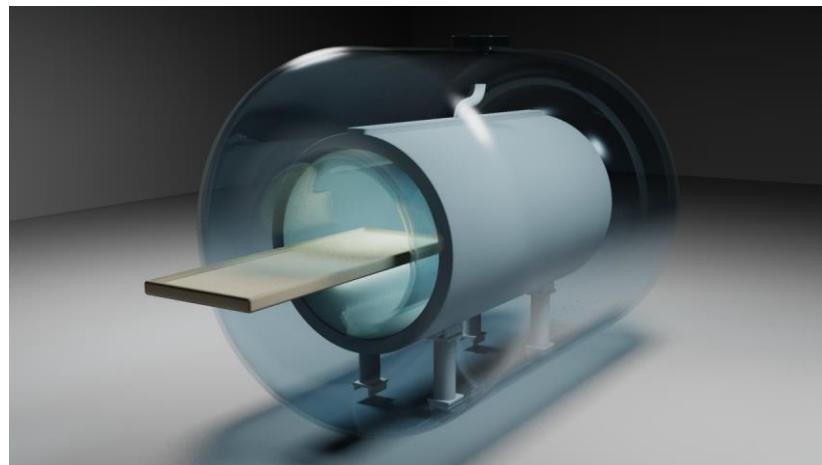
3. Results

4. Conclusion



1. Introduction

- Regenerative cryocoolers provide localized cooling
- Cryogenic applications require distributed cooling
 - Superconducting magnet: accelerators, MRI
 - Length scale ~ 1 meter



1. Introduction

□ Options for distributing the cooling power

- Metallic materials or component materials:

Copper, Aluminum.

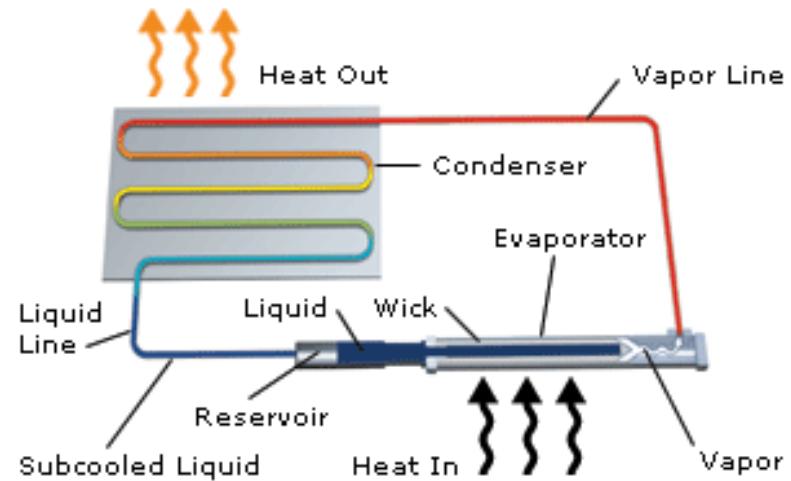
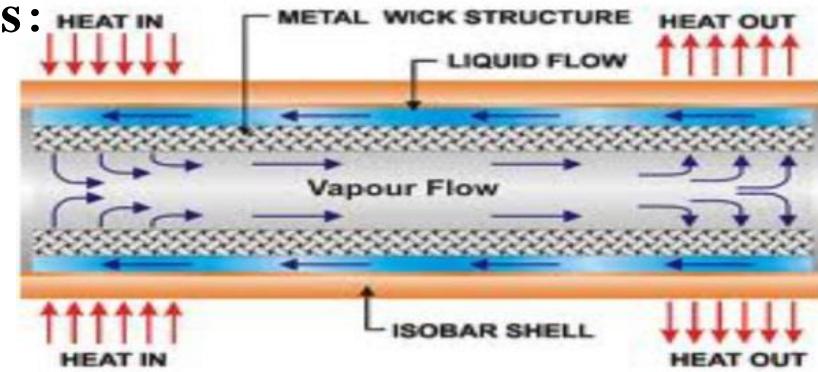
$$\text{Cu}_{100}(4\text{K}): Q=1\text{W}, \nabla T=1.5\text{K/m} \longrightarrow A \sim 10\text{cm}^2$$

- Cryogenic gas cooling
- Heat Pipe

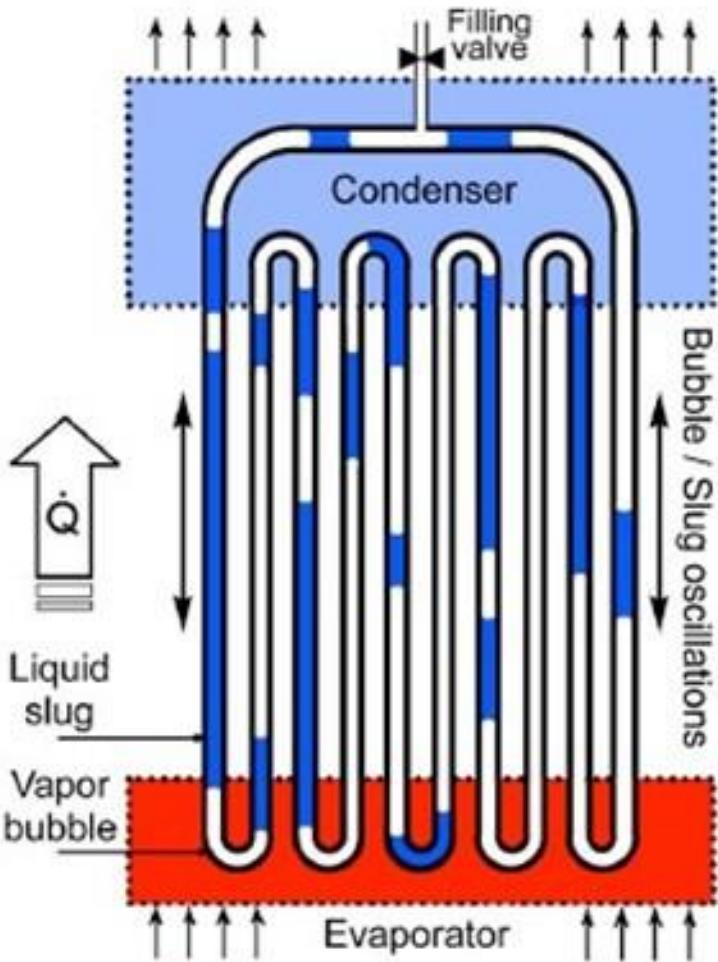
Conventional Heat Pipe

Capillary Loop Pipe

Pulsating Heat Pipe(PHP)



1. Introduction of PHP



- First developed in 1990 by Akachi
- Multiple loops of capillary tubing (no wicking structure)
- Partially filled with heat transfer fluid-alternating vapor slugs and liquid plugs
- Oscillatory and circulatory motions effectively transfer heat from evaporator to condenser
- Worldwide interest for room temperature applications

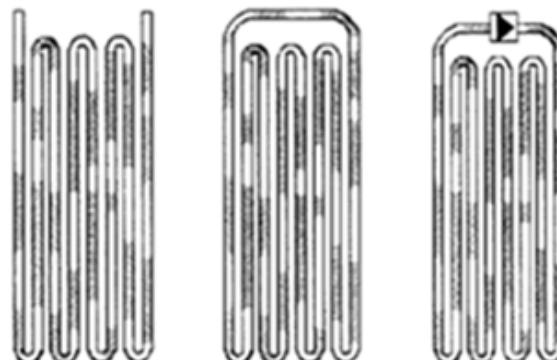


1. Introduction of PHP Review

Instituite	Working fluid	Capillary pipe		Turn number	Filling ratio %	Heat load W	Inclination °	Thermal conductivity W/(m×K)
		Material	Din mm					
University of Missouri	N ₂	Cu	1. 65	8	48	20. 5~380. 1	0	11600~26100
CEA-INAC/SBT(France)	He	Cu-Ni	0. 5	5	—	0. 015~0. 145	0~40	18700
	H ₂		0. 78	5	31~80	0~1. 2	90	500~3000
			1. 58	5	50~72. 2	0. 588~10	-90/- 45/0/45/90	2220~11480(90/45/0°)
Graduate University for Advanced Studies /National Institute for Fusion Science(Japan)	N ₂	SSL	0. 78	5	17~70	0~7	90	5000~18000
	Ne		0. 78	5	16~95	0~1. 5	90	1000~8000
			1. 58	5	50. 6~86. 1	0. 588~16	-90/- 45/0/45/90	5100~19440(90/45/0°)
University of Wisconsin-Madison	He	SSL	0. 5	32	4~26. 5	0. 003~0. 086	0	1320~2457
Technical Institute of Physics and Chemistry	He	SSL	0. 5	4	54	~1. 18	0/90	3000~17000
Institute of Electrical Engineering	N ₂	SSL	0. 9	5	50	1~22	-90/0/90	2500~16000

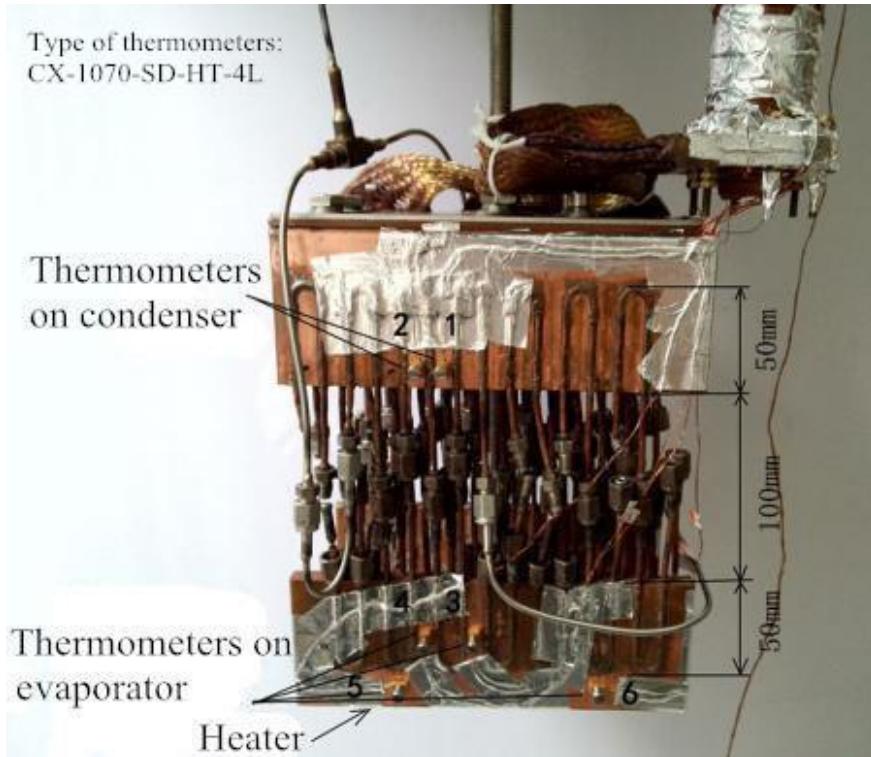


1. Introduction of PHP Influencing Factors

Factors	Fluid Properties	Surface tension σ , liquid & vapor densities ρ_l, ρ_v Capillary force	$Bo = d \sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}} < 2$
		Saturation line $\frac{dP}{dT_{sat}}$ latent heat	Driving force, Start of PHP
		Specific heat c_p	Sensible heat carried by slugs and plugs
		Viscosity coefficient μ_l, μ_v	Pressure drop along the walls
		Prandtl, Pr_l, Pr_v	Inertial forces of liquid slugs
	Geometry	Diameter, Loop length, tube shape, number of loop	
		Configuration	
Filling ratio	20%-80%		
Orientation	Critical number : $N > 16$		
Heat input			



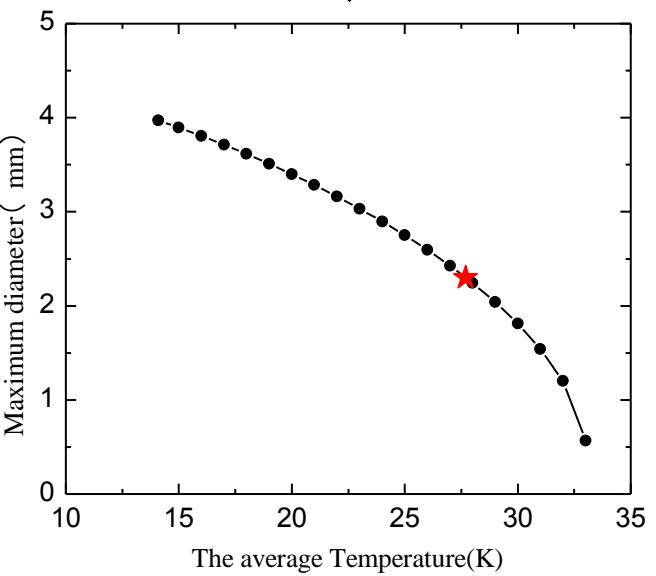
2. Experimental Setup



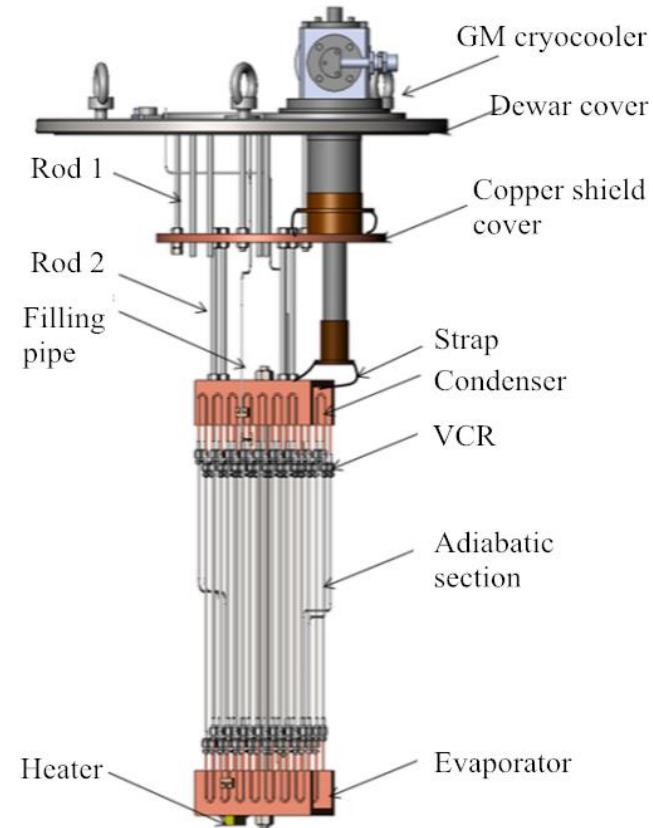
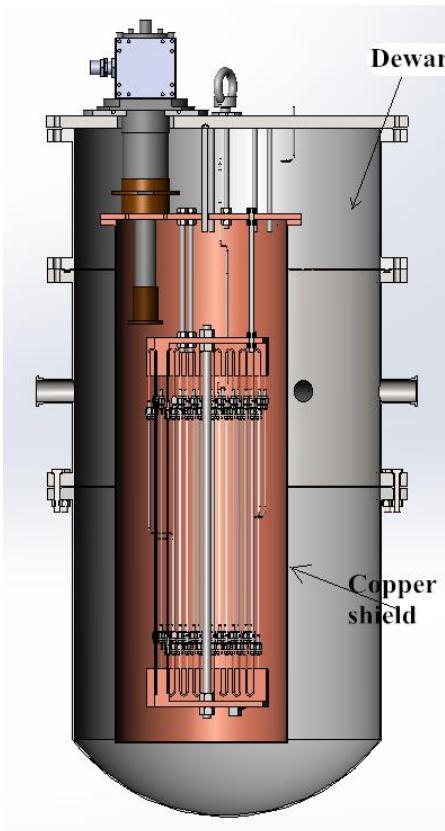
Number of turns \rightarrow Gravity

Length of adiabatic section \rightarrow Performance over long distance

$$Bo = d \sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}} < 2$$



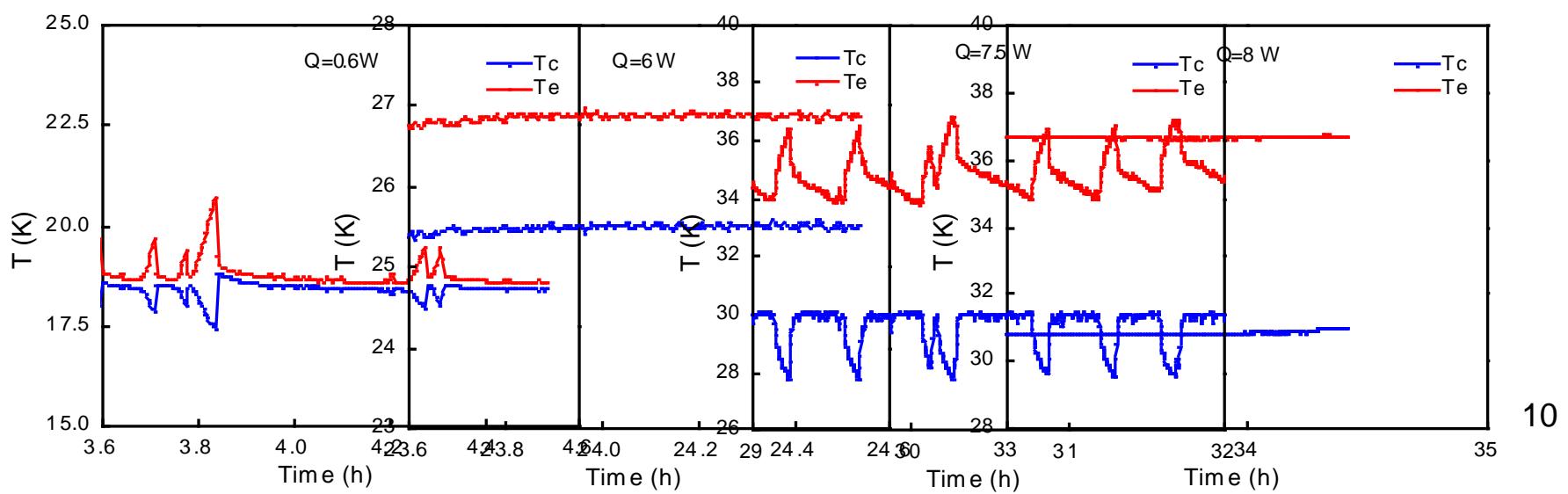
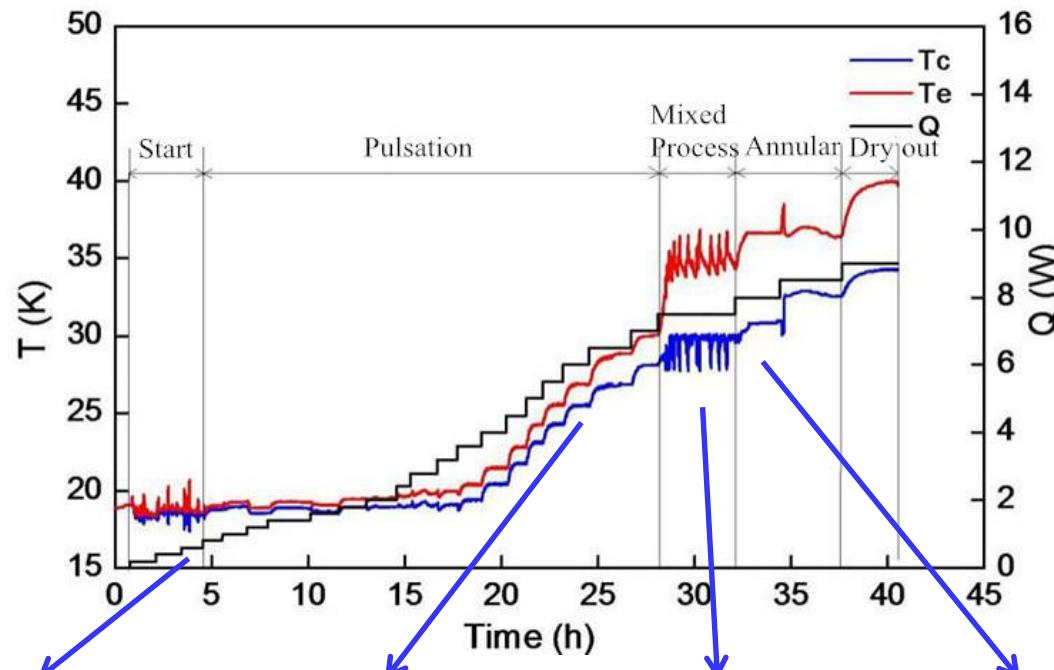
2. Experimental Setup



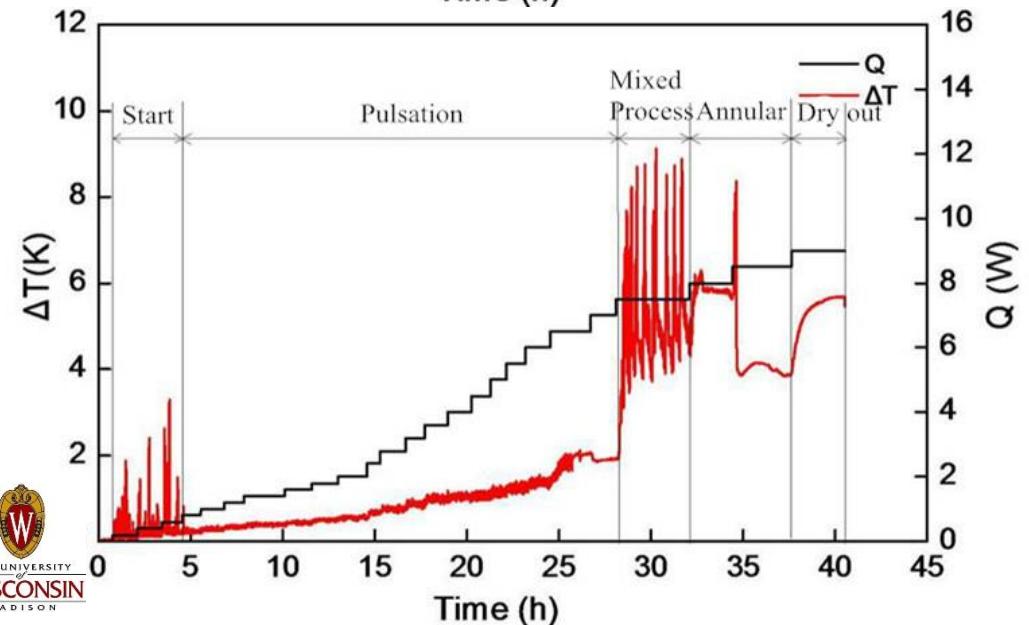
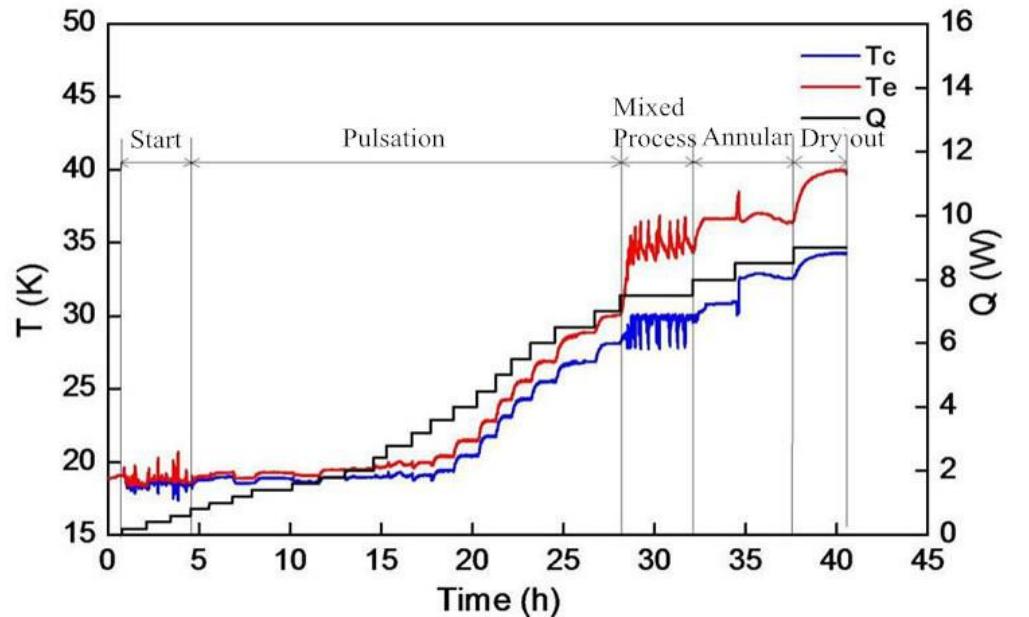
Component	Parameter
Cryocooler	KDE410: 1W@4.2K
Shield	Copper, $D_{in}=316\text{mm}$, $H=980\text{mm}$, $\delta=2\text{mm}$
Condenser/Evaporator	Copper, $L=200\text{mm}$, $H=70\text{mm}$, $\delta=10\text{mm}$
Capillary Pipe	Copper, Adiabatic Section-SSL, $D_{in}=2.3\text{mm}$, $D_{outer}=3.2\text{mm}$
Filling Pipe	SSL, $D_{in}=2.3\text{mm}$, $D_{outer}=3.2\text{mm}$



3. Results FR=51%



3. Results FR=51%



The temperature difference fluctuates and is sometimes big in the Start process.



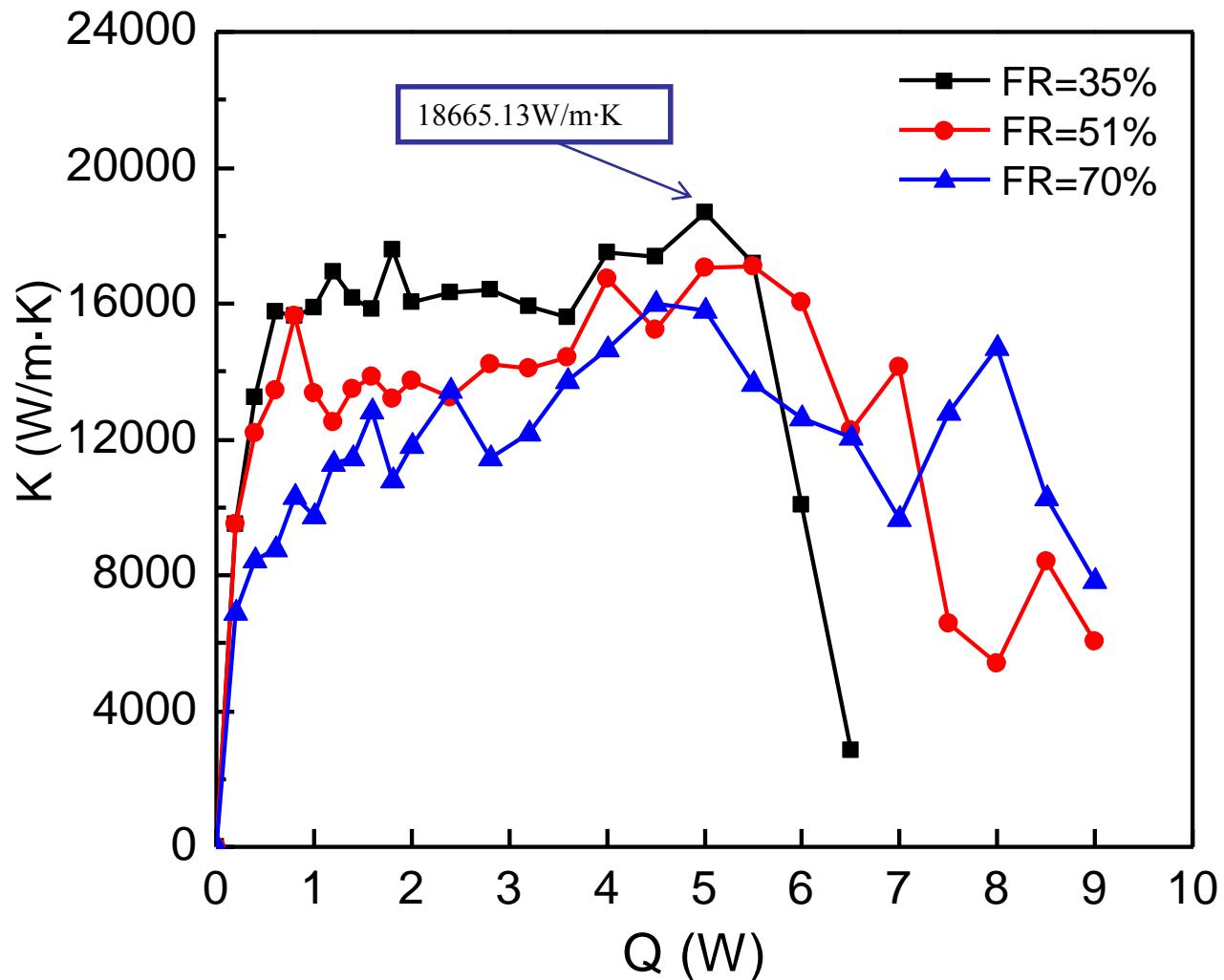
3. Results

Q _{evaporator} (W)	Q _{cold end} (W)	T _{cold end} (K)	T _c		T _e			
			T1(K)	T2(K)	T3(K)	T4(K)	T5(K)	T6(K)
0	15.3	18.49	19.01	19.03	19.08	19.04	19.04	19.07
0.2	14.3	17.32	18.30	18.32	18.41	18.37	18.37	18.40
0.4	13.8	17.12	18.58	18.61	18.74	18.70	18.69	18.73
0.6	13.25	16.47	18.39	18.42	18.60	18.55	18.55	18.58
0.8	13	16.38	18.79	18.82	19.03	18.97	18.97	19.01
1	12.5	15.96	18.96	19.00	19.30	19.23	19.24	19.28
2	8.5	13.24	18.95	18.99	19.57	19.48	19.49	19.54
3.2	2	9.64	19.04	19.11	20.00	19.88	19.91	19.97
4	0	8.92	20.44	20.50	21.45	21.31	21.35	21.42
5	0	9.61	23.09	23.16	24.32	24.16	24.21	24.29
6	0	10.33	25.45	25.51	26.99	26.82	26.88	26.96
7	0	11.13	28.08	28.16	30.09	29.92	29.99	30.08
8	0	11.74	30.94	31.02	36.72	36.56	36.65	36.70
9	0	12.55	34.23	34.32	40.00	39.85	39.96	39.99

The temperature at different locations on the evaporator is essentially uniform. The condenser behaves the same way.



3. Results



It seems that the best thermal performance corresponding filling ratio will occur for filling ratios between 30% and 50%.



4. Conclusion

- Conduct experiments, and the results confirm that the PHP critical diameter formula is suitable for a hydrogen PHP
- The thermal performance of the hydrogen PHP is investigated for filling ratios of 35%, 51%, 70% at different heating power
- The effective thermal conductivity of hydrogen PHP achieves $18665.13 \text{W/m}\cdot\text{K}$ when heat inputs is 5W, at this time, the temperature difference between the condenser and evaporator is about 1K



Acknowledgement

This work is financially supported by:

- I. Natural Science Foundation of China (No.51376157)
- II. "Thousand Expert Plan" of Zhejiang Province
- III. The National Magnetic Confinement Fusion Program
(2015GB121001)



**Thanks for your
attention**