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INVESTIGATION OF SUPER TUBE STRUCTURE AND PERFORMANCE (POSTPRINT)

Quinn Leland and Rengasamy Ponnappan

Energy & Power Systems Branch
Energy/Power/Thermal Division

Lanchao Lin

University of Dayton Research Institute

Edward Mahefkey

University of Central Florida

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PROPULSION DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251
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Quinn Leland and Rengasamy Ponnappan (AFRL/RZPE)
Lanchao Lin (University of Dayton Research Institute)
Edward Mahefkey (Unviersity of Central Florida)

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14. ABSTRACT
A new kind of heat transport device introduced by an inventor is intriguing the heat pipe community for the past several years. This device with the resemblance of the hermetically sealed structure and design of a conventional heat pipe or thermosyphon is claimed as thermally superconductive and offers solid state mode of heat transport. A host of speculations about this claim was emerging among research agencies that included academic and government laboratories. In order to explore the potentials of this device, recently Air Force Research Laboratory Propulsion Directorate's Power Division procured super tube hardware and conducted instrumented performance tests and dissection examination of the structure and inside contents. Heat transport performance test results of one stainless steel super tube and dissection, metallurgical/spectrographic examination of several copper and stainless steel super tubes are presented here. In conclusion, this investigation did not find anything substantive in these devices to validate any new phenomenon or breakthrough in heat transport capacity that exceeded what the state of the art heat pipe technology can offer.

15. SUBJECT TERMS
super tube, Qu tube, heat pipe, thermosyphon, performance test, tilt test

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Quinn Leland and **Rengasamy Ponnappan***
Propulsion Directorate
Air Force Research Laboratory
Wright-Patterson AFB, Ohio 45433-7251 USA
quinn.leland@wpafb.af.mil; rengasamy.ponnappan@aoard.af.mil

Lanchao Lin
University of Dayton Research Institute
300 College Park, Dayton, Ohio 45469-0179 USA
lanchao.lin@wpafb.af.mil

Tom Mahefkey
University of Central Florida,
Dept of Mechanical, Materials and Aerospace Engineering , Orlando, Florida 32816-2450 USA
qtom@bellsouth.net

ABSTRACT

A new kind of heat transport device introduced by an inventor is intriguing the heat pipe community for the past several years. This device with the resemblance of the hermetically sealed structure and design of a conventional heat pipe or thermosyphon is claimed as thermally superconductive and offers solid state mode of heat transport. A host of speculations about this claim was emerging among research agencies that included academic and government laboratories. In order to explore the potentials of this device, recently Air Force Research Laboratory Propulsion Directorate's Power Division procured super tube hardware and conducted instrumented performance tests and dissection examination of the structure and inside contents. Heat transport performance test results of one stainless steel super tube and dissection, metallurgical/spectrographic examination of several copper and stainless steel super tubes are presented here. In conclusion, this investigation did not find anything substantive in these devices to validate any new phenomenon or breakthrough in heat transport capacity that exceeded what the state of the art heat pipe technology can offer.

KEY WORDS*:* Super tube, Qu tube, heat pipe, thermosyphon, performance test, tilt test

1. INTRODUCTION

Technology need exists for efficient heat transport devices for aerospace applications. In pursuit of such a high performance device, in 2003, researchers at NASA LaRC considered a newly patented idea of a 'super tube' for their design of a heat exchanger for fuel cell system assumed in an emissionless aircraft design study[1] [Alexander NASA CR]. At this time, the super tube, also named 'Qu tube' after the inventor, Dr YuZhi Qu, was gaining popularity in thermal researchers community. Alexander wrote in his report apparently referring to the inventor's claims as follows: **"**Super tubes have been manufactured up to 75 ft in length and 6 inches in diameter. The tube itself can apparently be any material capable of being hermetically sealed and that will not leak. The heat transfer is accomplished by an extremely thin layer of a complex mixture of chemicals described in several patents. The heat transfer capabilities of these devices have reportedly been rigorously tested by reputed researchers. These devices are claimed to transport heat internally without a temperature gradient and could therefore be classified as a 'heat superconductor.' Evidence of the functioning of these tubes was presented by Dr. Qu's

* Author for correspondence;
Present address: Asian Office of Aerospace Research and Development, Air Force Office of Scientific Research, Tokyo, Japan

associates by laboratory demonstrations." UAH in 2006 [2] and Entrekin in 2008 [3] reported some preliminary data of the super tube tests carried out at The University of Alabama in Huntsville without any conclusive results. TAMU [4] [private communication] conducted extensive performance tests on a 12 inch long and 0.25 inch diameter copper super tube.

All these studies gave inconclusive and mixed opinions about the super tube device in general. The present study is aimed to shed some light on this new device and examine the claims made in the patents to the benefit of the thermal community. Also, in the absence of manufacturer's certification of the hardware, the authors would like to state that the question of authenticity of the hardware procured for this study is left to the reader's professional judgment.

2. 'SUPER TUBE' PATENT CLAIMS

Dr. YuZhi Qu, the inventor of super tubes, has several earliest patents and patent application publications as listed below:

- Chinese patent CN 1048593 dated January 16, 1991(First patent filed in August 3rd, 1989)
- International application publication WO 98/19859, May 14, 1998
- US 6,132,823 dated Oct 17, 2000
- US 6,811,720 B2 dated Nov 2, 2004
- US patent application publication US 2005/0056807 A1, Mar 17, 2005
- US 6,916,430 B1 dated Jul 12, 2005

Patents describe an inorganic solid state "super conducting heat transfer medium" and its possible uses. Three-layer and one-layer designs for the heat transfer medium are proposed. The major claims of these patents are,

- Solid state (no liquid inside the tube)
- Super conductor of heat
- Can be designed for various temperature ranges of operation
- Transport heat without a temperature gradient
- Made in any dimension/geometry
- Made in a variety of materials

All US patents had been assigned to Capital Technologies as a result of legal process between US sponsor and the inventor.

US patent number 6,132,823 dated Oct. 17, 2000 [5] describes the three layer design.

First Layer: The first layer is **an anti-corrosion layer** that prevents etching of the inner conduit surface and prevents the inner conduit surface from producing oxides. It is comprised of, in ionic form, various combinations of sodium, beryllium, a metal such as manganese or aluminum, calcium, boron, and dichromate radical. This layer is absorbed into the inner wall a depth of 0.008 to 0.012 mm.

Second Layer: The second layer is called the **"active" layer** and conducts heat like a wire conducting electricity. It accelerates the molecular oscillation and friction associated with the third layer providing a heat transfer pathway for conduction. It is comprised of, in ionic form, various combinations of cobalt, manganese, beryllium, strontium, rhodium, copper, β-titanium, potassium, boron, calcium, a metal such as aluminum and dichromate radical. This layer forms over the inner wall a thickness of 0.008 to 0.012 mm.

Third Layer: The third layer is called the **"black powder" layer**. It generates heat and oscillates in concert with the other layers once an activation temperature of 38°C is reached. The powder is comprised of various combinations of rhodium oxide, potassium dichromate, radium oxide, sodium dichromate, silver dichromate, monocrystalline silicon, beryllium oxide, strontium chromate, boron oxide, β-titanium, and a metal dichromate, such as manganese dichromate or aluminum dichromate. This must be evenly distributed over the interior of the conduit.

In the patent the amount of the compound in each layer is described as the amount, in grams, of the compound placed in solution with water.

3. EXPERIMENTAL WORK AT AFRL

3.1 Description of test hardware

Four super tubes were obtained for performance and structure evaluation. Two of them were copper and two were stainless steel. See the tube dimensions on Table 1.

Table 1. Super tubes evaluated.

Tube	Material	Length	OD	ID

ID		(inch)	(inch)	(inch)
E	Copper	39	0.875	0.844
B	Copper	39	0.875	0.844
T	SS	39	0.750	0.688
Q*	SS	28	0.750	0.688

* Tube used for performance test

All four tubes were physically inspected before any testing. No obvious physical rupture or dent on the tubes. Then all four tubes were qualitatively checked, by holding one end with hand and inserting the other end into beakers with boiling and ice water, separately. The hand hold end was at top (a reflux orientation). When inserting into boiling water, the temperature increase was felt right away with tube B, T, and Q, not tube E. As we found out later during the destructive test, there were liquids inside tubes B, T, and Q, but no liquid inside tube E. When inserting into ice water, there was no noticeable temperature difference between copper tubes E and B, and SS tubes T and Q. But there was difference between copper tube and SS tubes, as you would feel by your hand if they were regular solid metal tubes.

Physically, tube Q looked like the best fabricated. Its end cap was beautifully done. So the authors decided to choose tube Q for performance test.

3.2 Performance test and results

The test tube, tube Q, was instrumented with type T thermal couples along the tube and across at several axial locations. See the test apparatus schematic diagram and TC designation numbers and locations in Figures 1a and 1b. One type J TC was placed at the heater end as over temperature cutout TC. The heat input was supplied to the evaporator section by a nichrome wire with high temperature insulation. The power supply was 60VDC at 15A. The uncertainty of input power measurement was less than 1%. The cooling to condenser section was supplied by water from a temperature controlled cool bath. The flow rate, in the range of 0.04-0.75gpm, was calibrated with an accuracy of 3%. There were copper sleeves between the tube and the heater wire and cooling jackets to unify evaporator and condenser section temperatures. These copper sleeves had slots on the internal surface for TC wires. Both cooling and heater jackets covered four inches of the tube. At several locations at the heater, condenser and adiabatic sections, three TCs were placed at the same axial location with one TC on top, one on bottom and one on the middle of the tube to check the temperature variation across the circumference. All TCs were calibrated again an ice point and to the accuracy of ±0.1ºC. Figure 2a shows the instrumented test tube, 2b the adiabatic section, 2c the heater, 2d the water jacket as cooler, and 2e the insulated test tube. Figure 3 shows the overall test apparatus.

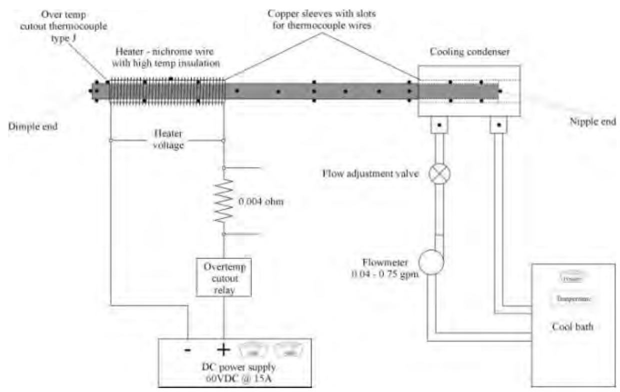


Figure 1a: Test Schematic Diagram

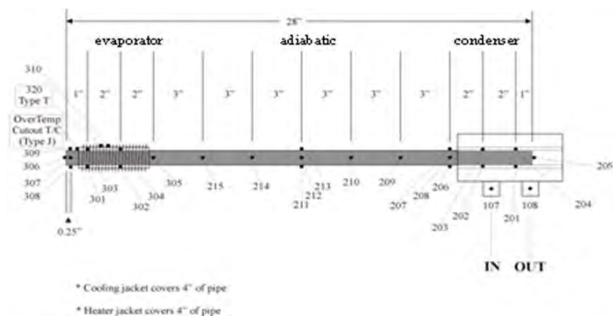


Figure 1b: Test tube TC locations

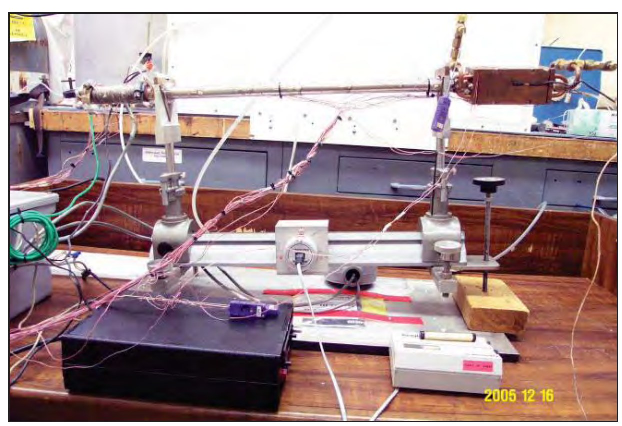


Figure 2a: Test tube instrumentation

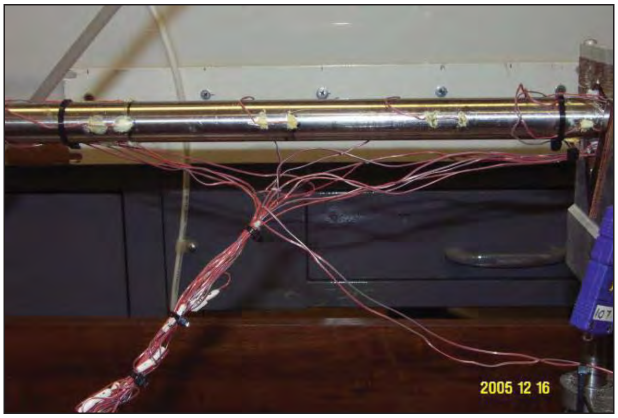


Figure 2b: Test tube adiabatic section

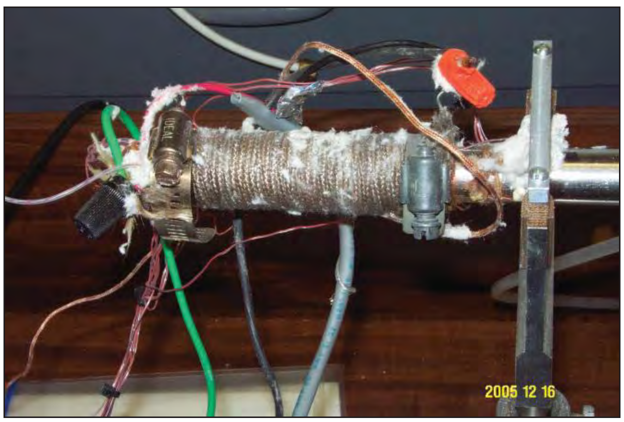


Figure 2c: Test tube heater: nichrome wire with high temperature insulation

Figure 2d: Test tube water jacket as cooler

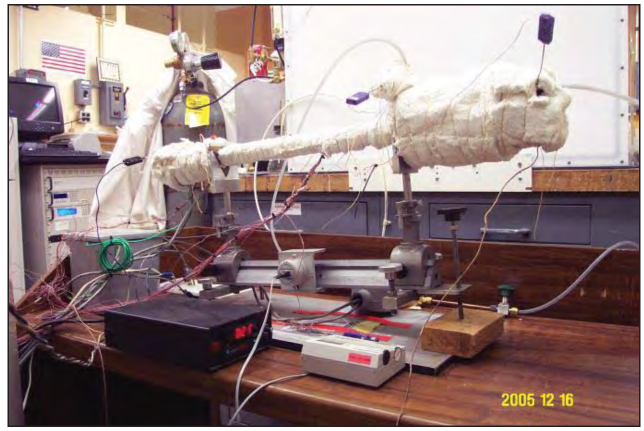


Figure 2e: Test tube wrapped with fiberfrax insulation

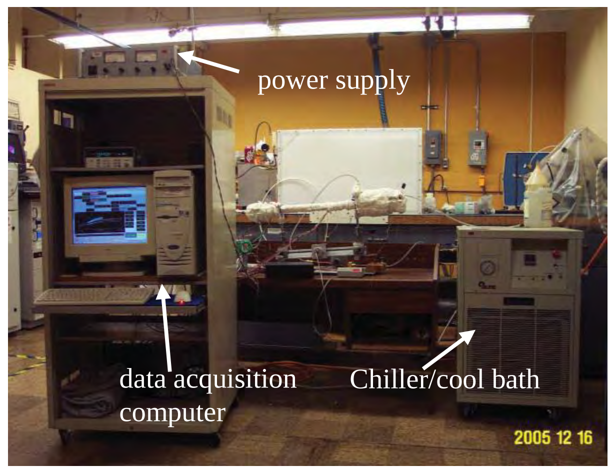


Figure 3: Test setup

The thermal performance evaluation tests varied three parameters: tube tilt angle, heat input, and coolant temperature. Table 2 shows the test matrix. The tilt angle was varied to check for gravity dependence. Tests were run as step functions allowing the tube to reach steady state at a new parametric setting. Figures 4a and 4b showed the temperature of evaporator, adiabatic section and condenser at various heat inputs at two tilt angles with condenser upward, a gravity assistant orientation. Figure 5, axial temperature distribution at different thermal loads, showed slight temperature gradient in wall temperature from the evaporator to the condenser, resembling a heat pipe temperature profile. Also, this super tube responded to the thermal loads as a heat pipe. Figure 6 showed the evaporator temperature run-off at very low heat input of 20W after 18 minutes when the tube was tilted at -4.7 degree (condenser at lower position). Among all the tests carried out, steady state was achieved at only thermosyphon position, or gravity assisted orientation.

Figure 7 showed the effective thermal conductivity of the tube. A limit was discovered for given parametric settings (function of tilt angle). A maximum k-effective of 15,000 W/mK was obtained, approximately 36 times of silver, far below the number claimed in patent US6,132,823 of 3,183,000 W/mK. The state of the art heat pipe technology has a k-effectives ranging from 50,000 to 200,000 W/mK [6].

Table 2 Test matrix

Tilt Angle °	Coolant Temperature_°C			
	no coolant	20	40	60
1	1 test Pmax=20W Tmax=64°C steady state not reached	No Tests	2 tests Pmax=300W Tmax=95°C Variation of tilt	No Tests
4.7	10 tests Pmax=20W Steady state reached only at 15W	1 test Pmax=350W Tmax=70°C Variation of tilt	4 tests Pmax=250W Tmax=85°C Variation of tilt Possible dryout	1 test Pmax=375W Tmax=120°C Dry-out Variation of coolant flow rate
-4.7	No Tests	No Tests	1 test Pmax=20W Steady state was not reached	No Tests
Total # of tests:	20	Note: 1. Tmax was determined from adiabatic temperature, TC212. 2. Tilt angle is positive when the evaporator is below the condenser and negative when above.		

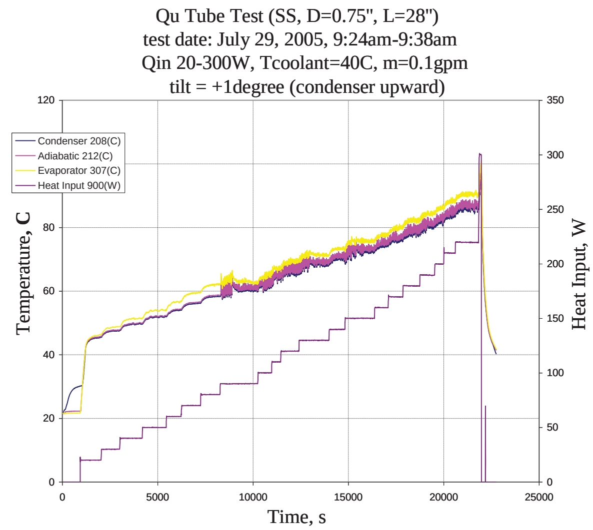


Figure 4a: Temperature distribution vs. heat input at tilt angle of +1 degree (condenser upward)

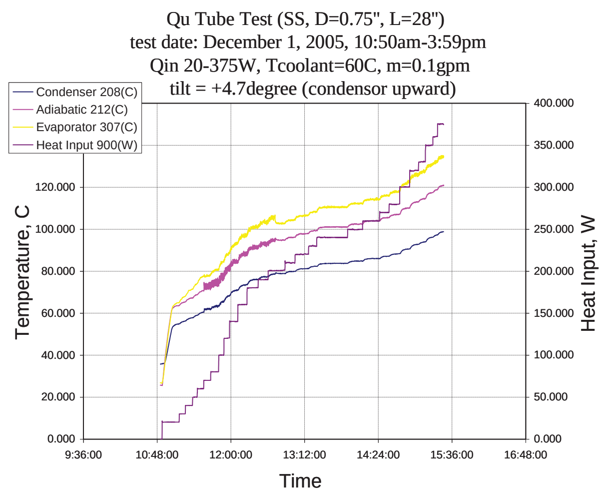


Figure 4b: Temperature distribution vs. heat input at tilt angle of +4.7 degrees (condenser upward)

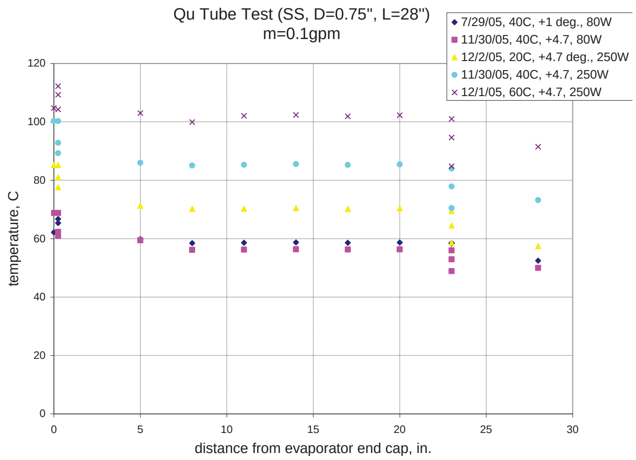


Figure 5: Axial temperature distribution at various heat inputs and at tilt angle of +1 and +4.7 degree (condenser upward)

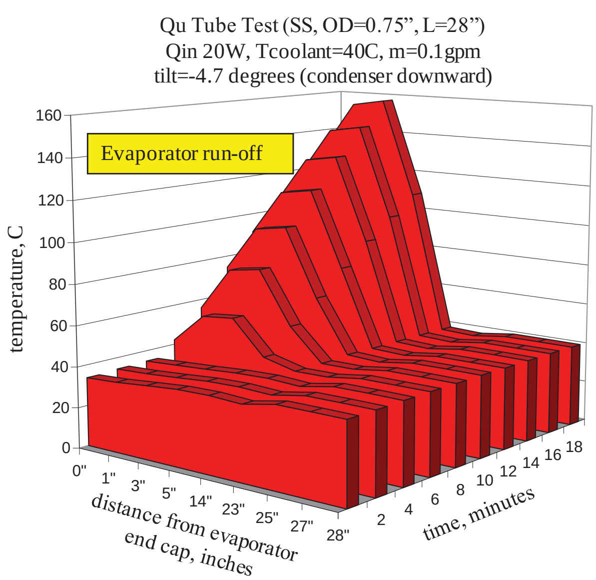


Figure 6: Evaporator temperature run-off at 20W heat input at tilt angle of -4.7 degree (condenser downward)

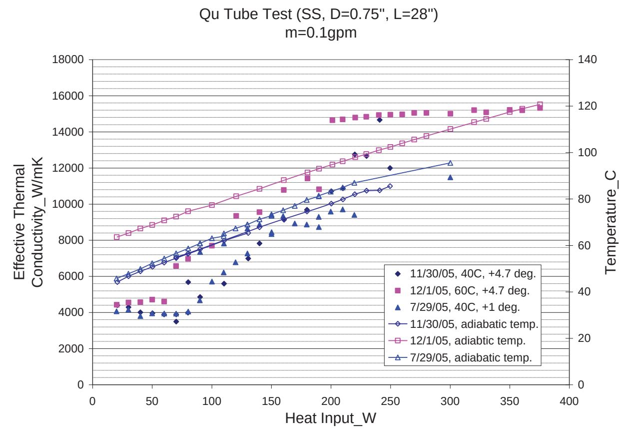


Figure 7: Effective thermal conductivity

3.3 Discussion of performance test results

Heat loss to the ambient was calculated as heat input at the evaporator from DC power supply minus the heat taken away through coolant flow at condenser. Heat taken away from the condenser was calculated by the calorimetry method. See Figure 8 the heat loss as function of heat input, a slope of 10%.

All the measurements were calibrated. Uncertainty of temperature readings from TCs was ±0.1ºC, flow rate <3%, heat input measured in power supply voltage and current <1%. Due to the tight uncertainty control of the measurements, the conclusion drawn in this paper was not compromised because of the lack of error bars in the plots and detailed system uncertainty analysis.

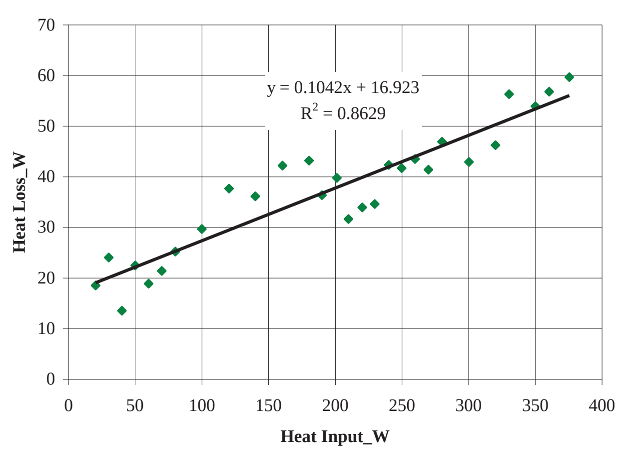


Figure 8: Heat loss to ambient

3.4 Destructive characterization

After the performance tests, all four tubes were sent to University of Dayton Research Institute Materials Lab for structural and destructive tests. Before cutting open, all tubes were externally x-rayed to look for solid within the pipes and went magnified image analysis. Then vacuum bags were connected to the tubes through puncture-valves, both were placed in dry ice bath to maintain low internal pressure (assuming that there was internal pressure); the valves were then turned to puncture into the tubes to collect any possible gases. It was found that there was no gas found from the cold tubes and there was no internal pressure higher than the ambient. Then all the tubes were cut open. See tubes' interior contents in Table 3. Table 4 listed other tests done on the tubes' interior composition.

For tube Q which was subjected to performance tests, Semi-quantitative spectra analysis showed the dried liquid residue was composed primarily of potassium, chromium, and oxygen with smaller amounts of calcium, sodium, and chlorine. Flame photometry analysis found a concentration of potassium and FIA found a concentration of hexavalent chromium. Ratio of potassium to chromium is close to that given by the formula weight of potassium dichromate. Desiccant test showed presence of water and DSC test showed a distinct boiling point of 100°C, see Figure 9.

No wicking material or any other solid except what was shown in Table 3 was present in the four pipes. Spectra analysis of stainless steel and copper tube interior wall samples showed the composition of the tube and oxidation, typical grain structure of stainless steel and copper tubing, see figure 10.

Table 3. Liquids found within the tubes

Tube E, copper, L=39", OD=0.875", ID=0.844",
no liquid found

Tube B, copper, L=39", OD=0.875", ID=0.844",
4 mL water solution with 1% K2CrO4

Tube T, stainless steel, L=39", OD=0.750", ID=0.688", *14 mL water solution with 1% K2Cr2O7*

Tube Q*, stainless steel, L=28", OD=0.750", ID=0.688", *10mL water solution with K2Cr2O7*

* Tube from performance tests

Table 4. List of tests on tubes interior composition

Test	Purpose
X-rays	Look for solid within pipe before destructive characterization.
Magnified image analysis	
Desiccant Test	Presence of water in vapor collected from tube.
Thermogravimetric analysis (TGA)	Estimate the percentage of solid in the liquid.
Spectra and elemental maps	Determine elemental composition of dried liquid and interior wall.
Infrared scans	Analyze liquid's dried residue
Differential Scanning Calorimetry (DSC)	Find boiling point of liquid.
Flow Injection Analysis (FIA)	Confirm presence of hexavalent chromium and potassium levels in the fluid once potassium chromate solution and potassium dichromate solution were suspected.

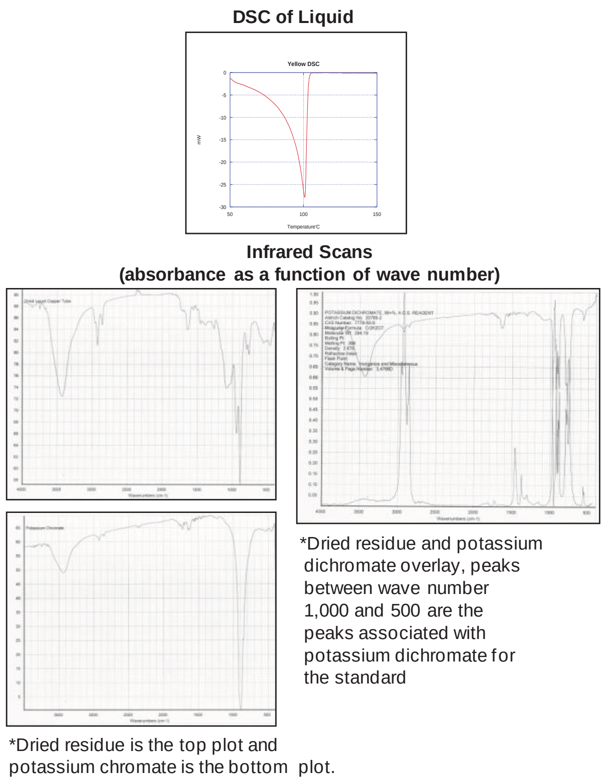
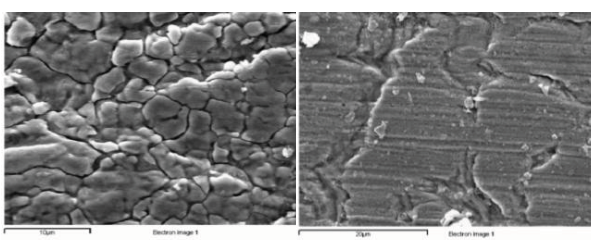


Figure 9: Liquid composition characterization



Stainless Steel interior wall, typical grain structure of stainless steel

Copper interior wall, marks on interior of wall are typical of drawn copper tubing

Figure 10: Spectra analysis of stainless steel and copper tube interior walls.

4. SUMMARY OF CONCLUSIONS

The performance study proves that the device tested is not a ‘super tube’. No ‘solid state’ type of working materials as claimed in the patent were found in the super tube tested. The super tube contained a working fluid; performed as a reflux thermosyphon; and the heat transport capacity was very poor without a positive tilt. Even as a thermosyphon, its capacity does not match that of an equivalent device designed according to the conventional heat pipe theory. Based on the destructive characterization of the super tubes, it is determined that no wicking material or solid was present within the tubes. However, potassium chromate or potassium dichromate in solution with water was found which are believed to be common passivating materials used in China for low carbon steel-water reflux boilers for corrosion prevention.

In conclusion, this investigation did not find anything substantive in these devices to validate any new phenomenon or breakthrough in heat transport capacity that exceeded what the state of the art heat pipe technology can offer. However, the authors would like to emphasize again that the tested tubes were not certified by either the inventor or the manufacturer as “super tubes”.

NOMENCLATURE

k-effective – effective thermal conductivity, W/mK
m – mass flow rate, gpm (gallon per minute)
K_2CrO_4 - potassium chromate
$K_2Cr_2O_7$ - potassium dichromate
L – length, inch
OD – outer diameter, inch
Pmax - maximum power input, W
Qin – heat input, W
Qu tube – super tube, super conductive tube
SS – stainless steel
TC - thermal couple
Tcoolant – coolant temperature, °C
Tmax - maximum temperature, ºC

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