BJRS

BRAZILIAN JOURNAL
OF
RADIATION SCIENCES
10-03A (2022) 01-15

Copper water heat pipe applied for Stirling engine

Santos[1] A.C., Guimarães[1,2] L.N.F., Leite[1,3] V.S.F.O.

[1] *Instituto Tecnológico de Aeronáutica (ITA), 12228-900, São José dos Campos, SP, Brazil*
[2] *Instituto de Estudos Avançados (IEAv)/Divisão de Energia Nuclear, 12228-001, São José dos Campos, SP, Brazil*
[3] *Instituto de Estudos Avançados (IEAv)/Divisão de Suporte Tecnológico, 12228-001, São José dos Campos, SP, Brazil*
[1] *anna.carolsantos21@gmail.com,* [2] *lamar.guima@gmail.com,* [3] *valnelsj@bol.com.br.*

ABSTRACT

Power generation in remote locations requires the advancement of efficient and long-lasting power generation technologies. One possible solution is a microreactor, which uses heat pipes to transport fission heat from a nuclear source to Stirling engines producing energy. In this context, TERRA (Advanced Fast Reactor Technology) project conducted by the Institute for Advanced Studies (IEAv) developed a Stirling engine and copper-water heat pipes for an initial study of both coupled devices. However, before using a nuclear source, it is necessary to understand the thermal behavior of the devices using an electrical heating source. Thus, the objective of this work is to test experimentally if a copper heat pipe can carry the necessary heat to activate the Free Piston Stirling engine. For this, it was necessary to develop a copper adapter to connect the pipe to the engine. The pipe was connected to the engine and temperatures were collected using T-thermocouples. The results of the experiments showed that the heat pipe was able to transport 28 W to the Stirling engine, which ran continuously. The maximum heat pipe temperatures were 253°C and the Stirling engine ran at 212°C in the hot source. Therefore, it was demonstrated that the IEAv´s copper-water heat pipe is capable of conducting the necessary heat to activate the IEAv´s Stirling engine and produce electricity. The results will form the basis for the future application of a nuclear source.

Keywords: **Heat pipe, Free Piston Stirling Engine, Microrreactor**.

ISSN: 2319-0612
DOI: https://doi.org/10.15392/2319-0612.2022.1876
Submitted: 2022-01-27
Accepted: 2022-09-29

1. INTRODUCTION

Humanity intends, in the coming decades, to build mission bases on the surface of Mars and the Moon. However, this requires the advancement of efficient and long-lasting energy generation technologies. Currently, nuclear power is the only technology capable of generating large amounts of energy for long periods safely and efficiently even in hostile conditions.

TERRA project conducted by the Institute for Advanced Studies (IEAv) researches technologies for the future development of advanced fast microreactors [1]. A microreactor is a small, portable reactor unit. This system uses the heat generated by nuclear fission to be converted to electricity using thermoelectric converters such as Stirling engines. It is a thermal machine that converts heat applied externally into electrical energy. However, the use of a nuclear source requires to shield the Stirling from neutron radiation. Therefore, it is necessary to use an intermediary device that transfers heat from the nuclear source to the engine. The heat pipe is one of such devices. It is a passive, two-phase flow sealed device, which rapidly transports a large amount of heat with the minimum drop in temperature [2].

A heat pipe scheme shown in the Figure 1 consists of a sealed metal pipe (envelope) with a capillary structure (wick) and a small amount of fluid in a partial vacuum (Working fluid). The length of the heat pipe is divided into three parts: evaporator, adiabatic, and condenser section.

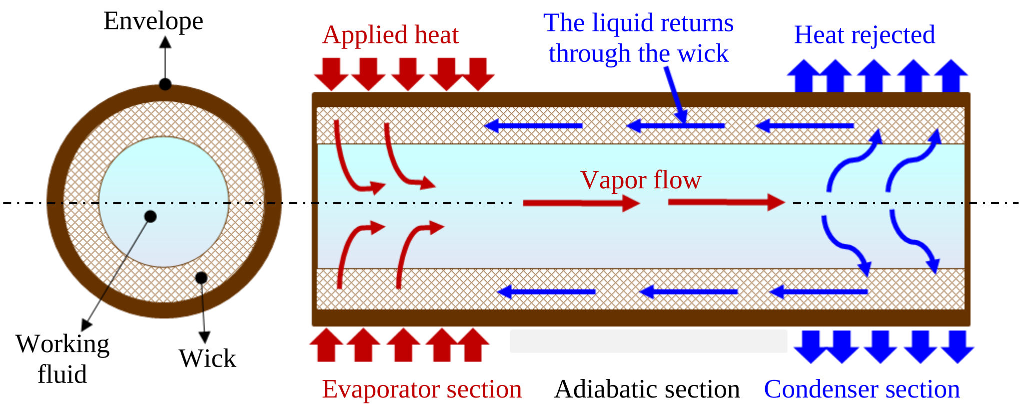


Figure 1: *Main components of a heat pipe.*

Heat inserted externally into the evaporator vaporizes the working fluid. The vapor expands towards the condenser carrying latent heat. In the condenser, the vapor condenses into a liquid, rejecting latent heat. The liquid is returned to the evaporator by gravity (thermosyphons) or by capillary forces in the wick (heat pipes). This cycle continues as long as there is a temperature gradient (hence pressure) between the evaporator and the condenser [3].

The main applications of heat pipes are in the cooling of electronic devices [3]. However, the practical application in Stirling engines and small reactors is still little discussed in the literature. Most research is developed by National Aeronautics and Space Administration (NASA), such as *Demonstration Using Flattop Fission* (DUFF) and *Kilopower Reactor Using Stirling Technology* (KRUSTY) experiments [4, 5, 6]. Currently, Kilopower concept shown in the Figure 2 is the most advanced concept of portable reactors. It uses alkali metal (Sodium) heat pipes to transfer fission energy from a solid block of fuel to the base of Stirling machines, which produce electricity. And it uses titanium water heat pipes to remove the waste heat and transport it to the radiators, to be rejected to space. NASA in partnership with the laboratory at Los Alamos tested the nuclear source and proved that these technologies were possible. However, it is recent research and with several opportunities for improvement.

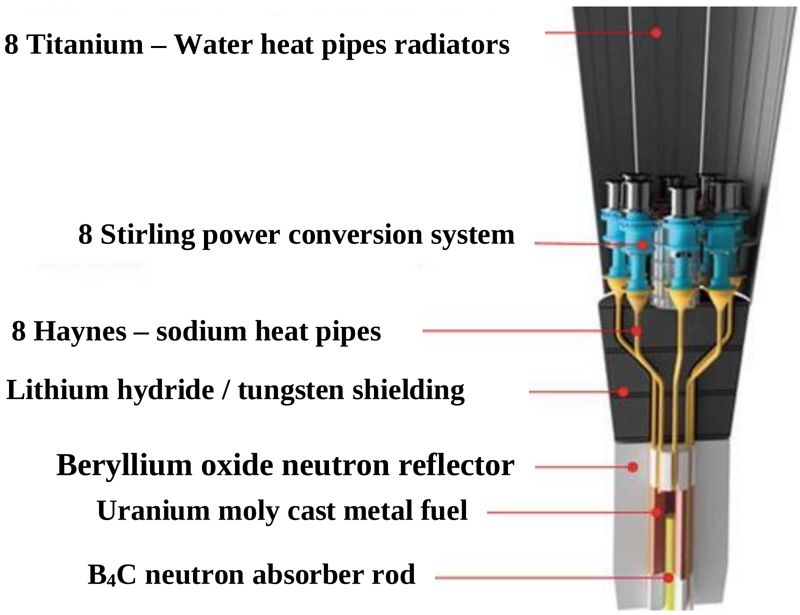


Figure 2: *Representation of Kilopower Reactor Using Stirling and heat pipes technology* [6].

The IEAv intends in the future to develop powerful microreactors analogous to Kilopower. However, research is needed first on Stirling machines, heat pipes and the integration of these technologies. In this context, the IEAv developed a Free Piston Stirling engine and 100 mesh copper water heat pipes [7] [8] [9]. Before carrying out nuclear tests, it is necessary to understand all the mechanisms that involve these technologies for better safety in nuclear tests. Thus, the objective of this work is to test experimentally if a copper heat pipe can carry the necessary heat to activate the Stirling engine as shown in the Figure 3. The pipe was heated using an electrical thermal belt. However, this experiment will serve as a basis for future work using a nuclear source.

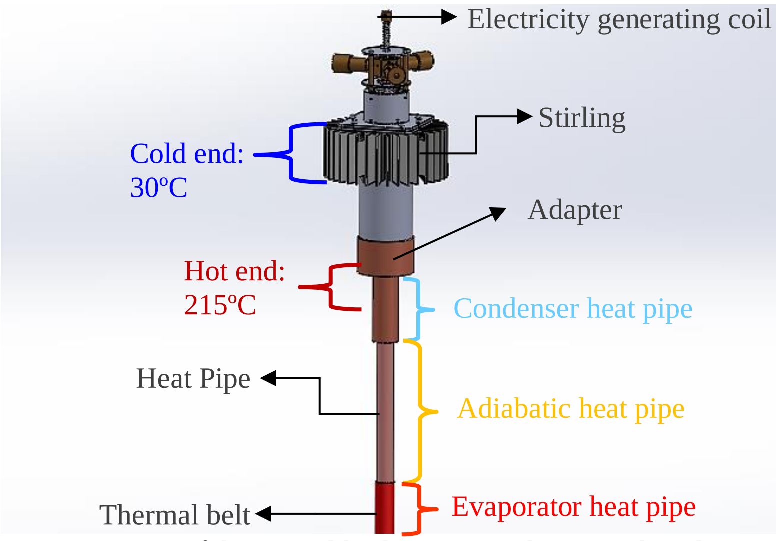


Figure 3: *Drawing of the assembly: heat pipe, adapter and Stirling engine.*

In previous works, it was obtained by simulation in the ANSYS transient thermal software that the heat pipe condenser should exceed a temperature of 220º [10-11]. This value is sufficient to conduct heat to the adapter and activate the Stirling engine. Also, the copper heat pipe evaporator of this work should not exceed the safety temperature of 270°C to avoid fractures and accidents. The authors tested the existing heat pipes in the IEAv at different inclination angles and amount of working fluid [11]. The results of these researches showed that the minimum volume of working fluid (deionized water) must be 87% of the evaporator volume. With this volume of fluid, the heat pipe operated similarly in all positions (0 – 90°) relative to horizontal.

2. MATERIALS AND METHODS

2.1. Stirling engine and adapter

The Stirling engine used in the experiment is a free-piston beta type as shown in Figure 4. It is composed of a working piston and a displacer which are aligned inside a heat exchanger, where the working gas is pressurized. Power is generated by heating and cooling the outside of the heat exchanger, which provides a temperature and pressure differential, generating the force needed to drive the pistons and convert kinetic energy into electrical energy [7].

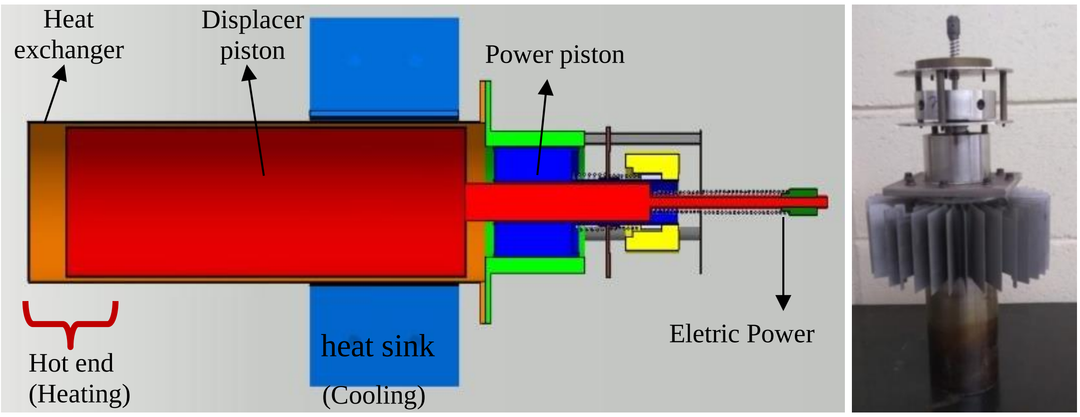


Figure 4: *Components of a Free Piston Stirling engine and assembled Stirling engine [7].*

The hot end of the Stirling engine should be approximately 215 °C for the engine to run continuously. Thus, a copper device shown in Figure 5, called an adapter, was developed to connect and transfer heat from the heat pipe condenser to the base of the Stirling engine.

Figure 5: *Three-dimensional drawing made in Solidworks of the designed adapter.*

2.2. Heat pipe

The heat pipe shown in the Figure 6 is composed of a copper envelope, a Brass screen-capillary structure and 69.8 ml (87% of the evaporator volume) of deionized water as the working fluid.

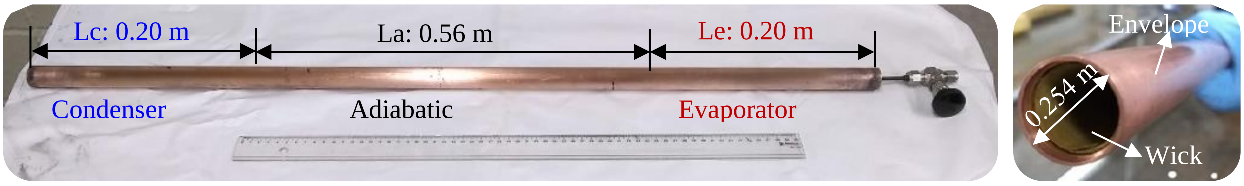


Figure 6: *Dimensions of the IEAv 100 mesh Heat Pipe used in this experiment.*

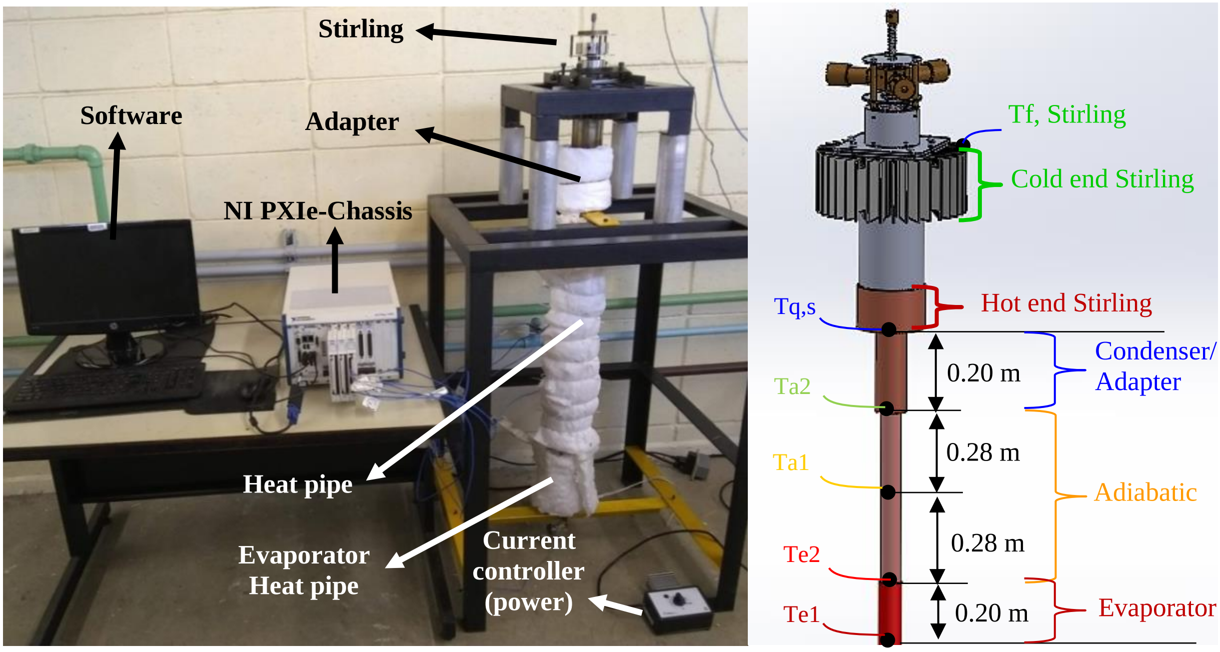
The adiabatic region of the pipes was isolated with an alumina ceramic fiber blanket (thickness 25 mm and thermal conductivity of 0.071 W/ (m K)) as shown in the Figure 7.

Figure 7: *Photo of the adiabatic region isolated with alumina ceramic fiber.*

The evaporator region was heated using a thermal heating belt (220 V) with a power controller. In addition, the belt was isolated by a ceramic fiber blanket as shown in the Figure 8.

Figure 8: *Thermal power controller and thermal tape for heating the evaporator heat pipe.*

The condenser region was connected to the copper adapter. The adapter was attached to the base of the Stirling engine and fixed to the support table. The setup of the experiment is shown in the Figure 9 (a). Furthermore, seven T-IOPE thermocouples were calibrated for temperatures range between 20 ºC and 300 ºC (Instrument uncertainty ± 1 ºC and coverage factor, k = 2). The T thermocouples were connected to the predetermined pipe positions shown in the Figure 9 (b). The NI PXIe-1082 chassis was used for temperature data collection. Finally, the software used to collect pipe temperatures was developed in Labview.



(a)...(b)

Figure 9: In (a) Experiment setup and in (b) representation of thermocouple positions.

With the temperatures collected, the graph of the device temperature distribution during the test was plotted, presented in Figure 10. In addition, the main operating limits that affect the transfer and functioning of the heat pipes were calculated: viscous, sonic, boiling, capillary were obtained by Eq. (1-5).

$$q_{viscous} = \frac{{d_v}^2 \cdot h_{lv} \cdot \rho_v \cdot p_v}{64 \cdot \mu_v \cdot \{[(L_e + L_c)/2] + L_a\}} \tag{1}$$

$$q_{sonic} = 0{,}474 \cdot A_v \cdot h_{lv} \cdot \sqrt{\rho_v \cdot p_v} \tag{2}$$

$$q_{entrainment} = A_v \cdot h_{lv} \cdot \sqrt{\frac{\sigma_l \cdot \rho_v}{2 \cdot r_{eff}}}, \tag{3}$$

$$q_{capillary} = \frac{\sigma_l \cdot \rho_l \cdot h_{lv}}{\mu_l} \cdot \frac{K \cdot A_w}{[(L_e + L_c)/2] + L_a} \cdot \left(\frac{2}{r_{eff}} - \frac{\rho_l \cdot g \cdot (L_e + L_a + L_c) \cdot (\cos \cdot \psi)}{\sigma_l}\right) \tag{4}$$

$$q_{boiling} = \left(\frac{2\pi \cdot L_e \cdot k_{eff} \cdot T_v}{h_{lv} \cdot \rho_v \cdot \ln\left(\frac{D_i}{D_v}\right)}\right) \cdot \left(\frac{2\sigma_l}{2{,}54 \times 10^{-6}} - P_c\right) \tag{5}$$

Where D_v is the vapor diameter (m), h_{lv} is the latent heat of vaporization (J/kg), ρ_v is the vapor density (Kg/m³), p_v is the vapor pressure (Pa), μ_v is the vapor dynamic viscosity (Kg/m s), L_e is the evaporator length (m), L_c is the condenser length (m), L_a is the adiabatic length (m), A_v is the cross sectional area of vapor diameter (m²), σ is the superficial tension (N/m), r_{eff} is the effective capillary radius, ρ_l is the liquid density (Kg/m³), μ_l is the liquid dynamic viscosity (Kg/m s), K is the wick permeability, A_w is cross-sectional area of the capillary structure [m²], g is the gravity (m/s²), ψ is the inclination angle of heat pipe, k_{eff} is the effective thermal conductivity (W/m K) obtained by Eq. (6), T_v is vapor temperature, D_i is the inner diameter (m), D_e is the external diameter (m), and P_c is the capillary pressure (Pa) [2-3].

$$k_{eff} = \frac{k_l \cdot [(k_l + k_w) - (1 - \varepsilon)(k_l - k_w)]}{[(k_l + k_w) + (1 - \varepsilon)(k_l - k_w)]} \tag{6}$$

k_l is the thermal conductivity of the working fluid (W/m K), k_w is the thermal conductivity of wick material (W/m K) and ε is the mesh porosity [2].

The thermal power transferred by the tube must be smaller than all of these limits to ensure that the heat pipe works without damage. The thermal power transferred by the heat pipe (Project) is defined by Eq. 7 [2].

$$q_{\mathrm{Project}} = \frac{\Delta \mathrm{T}}{\mathrm{R}} \tag{7}$$

Where ΔT is the difference of the evaporator and condenser wall temperature, R is the total thermal resistance of the heat pipe, defined by Eq. 8. This calculation considers all thermal losses during the experiment and external heat transfer resistances.

$$\mathrm{R} = \frac{1}{\mathrm{h_e} \cdot \mathrm{A_e}} + \left(\frac{2 \cdot \left[\ln\left(\frac{\mathrm{D_e}}{\mathrm{Di}}\right) + \ln\left(\frac{\mathrm{D_i}}{\mathrm{Dv}}\right) \right]}{2 \cdot \pi \left[L_e \cdot \mathrm{k_{copper}} + \mathrm{L_e} \cdot \mathrm{k_{eff}} + L_c \cdot \mathrm{k_{eff}} + \mathrm{L_c} \cdot \mathrm{k_{cooper}} \right]} \right) + \frac{1}{\mathrm{h_c} \cdot \mathrm{A_c}} \tag{8}$$

Where h_e is evaporator external convection heat transfer coefficient, h_c is condenser external convection heat transfer coefficient, D_i is the pipe inner diameter (m), D_e is the pipe external diameter (m), D_v is the pipe vapor diameter (m), L_e is the evaporator length (m), L_c is the condenser length (m), L_a is the adiabatic length (m), k_{copper} is pipe material thermal conductivity (W/m K), k_{eff} is the effective thermal conductivity (W/m K), A_c is condenser side section area and A_e is evaporator side section area

3. RESULTS AND DISCUSSION

The activation temperature of the Stirling engine is approximately 215 °C. The activation temperature of the Stirling engine is approximately 215 °C. Therefore, the condenser heat pipe temperature must be higher than 220 °C according to previous studies in thermal simulation in thermal transient ANSYS code [10]. Tests performed with the separate heat pipe (uncoupled at Stirling) showed that for it to reach 222 ± 1 ºC on the condenser, the evaporator would need at least 256 ± 1 °C.

The temperature differential between evaporator and condenser was similar as shown in Figure 10. In Figure 10 watch the dashed pink color line. The heat pipe operated in both horizontal and vertical positions. Note that the increase in power applied to the evaporator causes an increase in the temperature differential between the evaporator and condenser. As power is applied to the evaporator, the heat pipe took approximately 5400 s to reach steady-state.

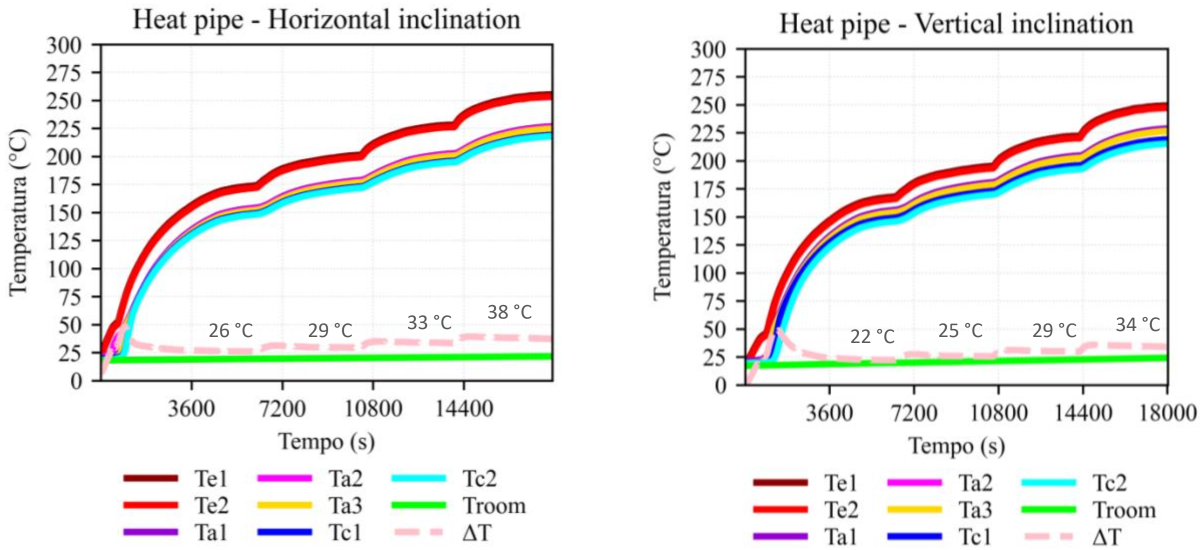


Figure 10: *Temperature distribution in the heat pipe operating in horizontal and vertical position.*

Figure 11 shows the operating limits of the heat pipe according to the temperature increase in the evaporator region.

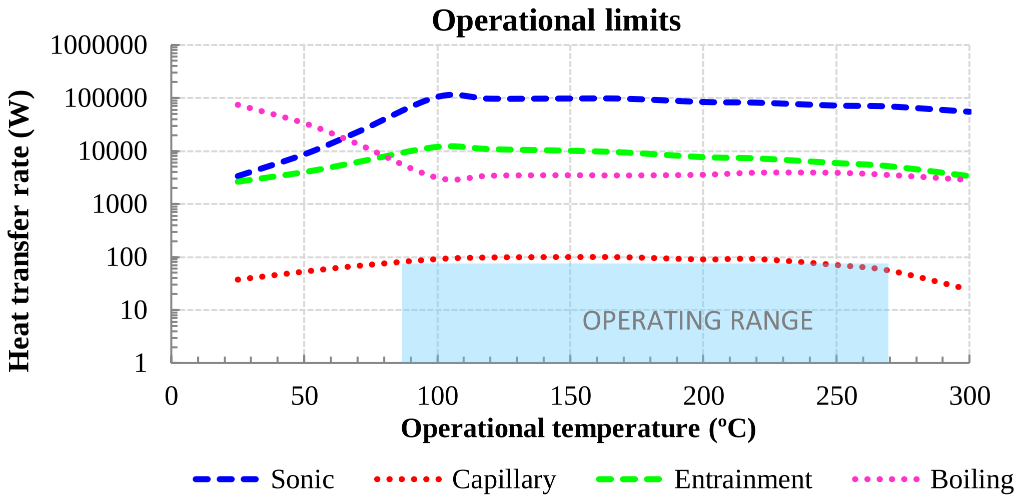


Figure 11: Main operating limits of the heat pipe.

The smallest operating limit value is the capillary limit. The capillary limit is the maximum capacity of the capillary structure to provide sufficient capillary pressure for the circulation of the working fluid within the pipe. This is the limiting factor in the horizontal position or position where gravity is not favorable. The capillary limit decreased with increasing tube operating temperature. The low capillary limit indicates that the copper pipe with a 100-mesh capillary structure, in the dimensions developed, is not the most suitable for the tested temperature. Therefore, the test with the complete set (Heat pipe, adapter, and Stirling) was performed in the vertical position so that the limit was not reached.

In the complete test, the evaporator temperature was gradually increased from 23°C to 253°C. The temperature distribution along the heat pipe coupled to the Stirling engine is shown in Figure 12. The total test time was approximately 6.5 hours. The evaporator reached 253 °C, and the condenser reached 215 °C. Therefore, the Stirling engine activated at 212 °C. The engine ran continuously without interruption. This temperature was close to the thermal simulation in thermal transient ANSYS code [10].

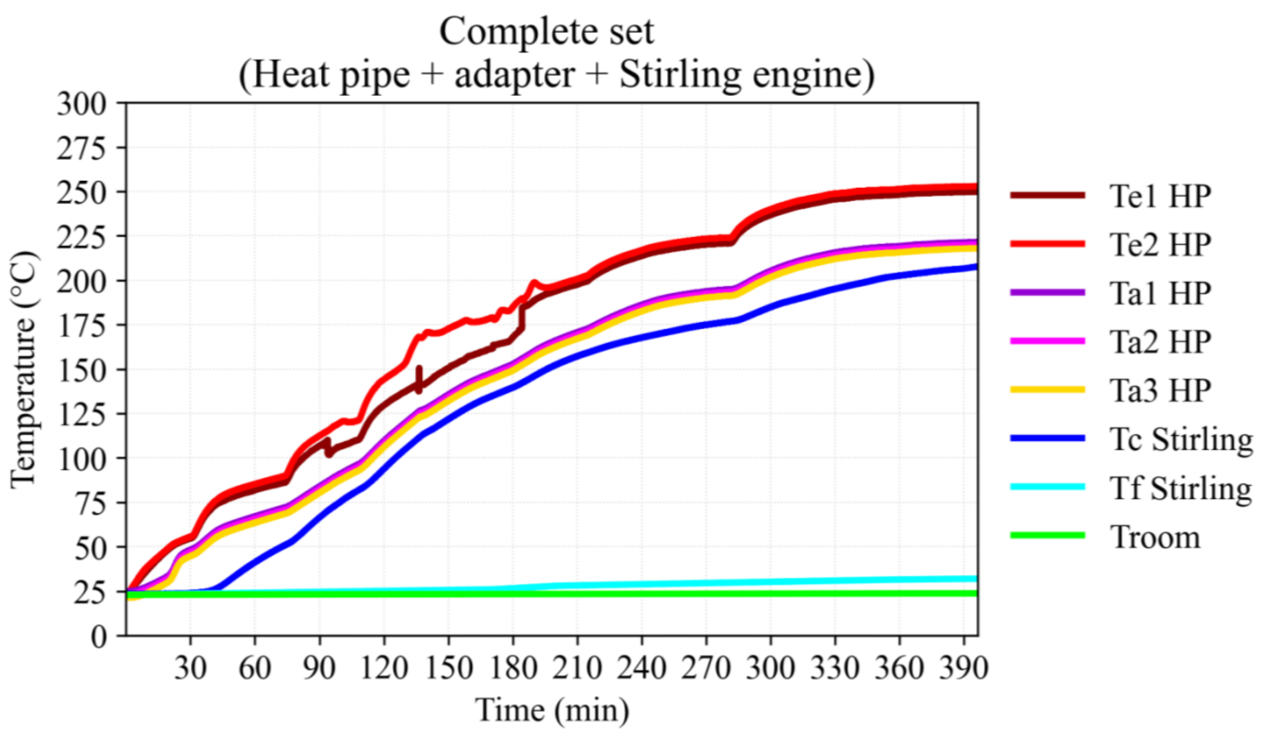


Figure 12: *Temperature distribution along the heat pipe (HP), Stirling engine and room.*

The heat pipe coupled to the Stirling presented a thermal behavior very similar to the tests performed with it uncoupled, as shown in Table 1.

Table 1: Comparison between heat pipes coupled and uncoupled at Stirling.

	Te (°C)	**Ta (°C)**	**Tc (°C)**	**ΔT**	**q (W)**
heat pipe uncoupled at Stirling	256	230	222	34	19
heat pipe coupled at Stirling	253	222	215	38	28

However, in the case of the heat pipe coupled with the Stirling engine, it was necessary to insert more thermal energy into the evaporator to reach the same temperature. The uncoupled heat pipe required 275 W in the power controller for heating the thermal belt to reach 253 ± 1 °C in the evaporator. The heat pipe with the Stirling engine needed 336 W to reach a temperature of 256 ± 1 °C. This is due to greater heat dissipation transferred from the pipe to the adapter than the uncoupled heat pipe. This means that condensation occurs faster in the coupled pipe than the uncoupled pipe. Thus, to maintain the evaporation and condensation cycle, more heat is needed to heat the fluid in the evaporator and transport it to the condenser.

The thermal power of the heat pipe to Stirling was 28 W. This value considers the external resistances with the environment. In comparison, the grooved titanium-water heat pipe used in Kilopower carries 125 W [6]. Although copper has a higher conductivity than titanium, the copper heat pipe in this work has a high wall thickness (1.25 mm) compared to titanium (0.50 mm), which impair heat transfer.

Finally, the heat pipe coupled to the Stirling engine did not show any failures and did not reach any operational limits. The power transferred by the heat pipe (Project) was below all the operating limits as shown in Table 2. Therefore, the copper heat pipe transferred the heat needed to start the Stirling engine successfully.

Table 2: Operating limits (W) heat pipe coupled at Stirling

Te (ºC)	**Project (W)**	**Boiling (W)**	**Entrainment (W)**	**Sonic (W)**	**Viscous (W)**
253	28	4102	5633	56211	$5,7\times 10^{10}$

4. CONCLUSION

With this work it was proved that the copper heat pipe is capable of transferring the thermal energy needed to activate the Stirling engine, both built at IEAv. The heat pipe coupled at Stirling engine showed similar thermal behavior, when compared with the heat pipe uncoupled at Stirling. The heat pipe operating in vertical position did not reach any operating limits. The Stirling engine ran continuously when the heat pipe evaporator temperature reached 250 °C. Finally, the data obtained will serve as a basis for the study of the application of a nuclear source in the heat pipe evaporator.

ACKNOWLEDGMENT

This study was financed in part by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and the TERRA Project - Finance Code 001. Acknowledgments are provided to the IEAv for the use of the Laboratories and Felipe Euphrásio for the use of the heat pipe developed on his Master dissertation.

REFERENCES

[1] GUIMARAES L. N. F.; RIBEIRO G. B.; FILHO F. A. B.; NASCIMENTO J. A.; PLACCO G. M.; FARIA S. M. Technology Development For Nuclear Power Generation For Space Application. In: **INTERNATIONAL NUCLEAR ATLANTIC CONFERENCE**, 2015, São Paulo. Proceedings Meeting on Nuclear Reactor Physics and Thermal hydraulics (ENFIR), Rio de Janeiro: Associação Brasileira de Energia Nuclear (ABEN), 2015. p. 1-11.

[2] REAY, D. A.; KEW, P. A. **Heat pipes: theory, design and applications**, 5th ed. Oxford: Elsevier's Science & Technology, 2006.

[3] ZOHURI, B. **Heat Pipe Design and Technology: Modern Applications for practical thermal management**, 2nd ed. New York: Springer Publishing company, 2016.

[4] GIBSON, M et al. **Heat Pipe Powered Stirling Conversion for The Demonstration Using Flattop Fissions (DUFF) test**. NASA/TM Report 216542, Washington, DC: NASA, 2013. 18 p.

[5] GIBSON M.; POSTON D. I; MCCLURE P.R. The Kilopower Reactor Using Stirling Technology (KRUSTY) nuclear ground test results and lessons learned. In: **AIAA PROPULSION AND ENERGY FORUM**, 2018, Cincinnati. Proceedings […]. Reston: AIAA, 2018. p. 1-12

[6] GIBSON M.; OLESON S.R.; POSTON D.I; MCCLURE P.R. NASA's Kilopower Reactor Development and the Path to Higher Power Missions. In: **IEEE AEROSPACE CONFERENCE**, 2016, Big Sky. Proceedings […]. Big Sky: **IEEE Aerospace,** 2016. p. 1-13.

[7] SANTOS A C.; GUIMARÃES L. N. F.; LEITE V. S. F. O.; THEODORO R. Development of a free piston Stirling engine, In: **INTERNATIONAL NUCLEAR ATLANTIC CONFERENCE**, 2019, Santos. Proceedings Nuclear New Horizons: Fueling our future. Rio de Janeiro: Associação Brasileira De Energia Nuclear, 2019. p. 5123-5133.

[8] THEODORO R.; SANTOS, A. C.; LEITE V. S. F. O.; GUIMARÃES L. N. F. Stirling engine as a thermo electric converter for space systems. In: **INTERNATIONAL NUCLEAR ATLANTIC CONFERENCE**, 2019, Santos. Proceedings Nuclear New Horizons: Fueling our future. Rio de Janeiro: Associação Brasileira De Energia Nuclear, 2019. p. 5135-5145.

[9] EUPHRÁSIO F. P. A.; GUIMARÃES L. N. F. Procedures for analysis and construction of heat pipes in application to the TERRA project", In: **INTERNATIONAL NUCLEAR ATLANTIC CONFERENCE**, 2019, Santos. Proceedings Nuclear New Horizons: Fueling our future. Rio de Janeiro: Associação Brasileira De Energia Nuclear, 2019. p. 5202-5214.

[10] SANTOS A.C.; GUIMARÃES L. N. F.; LEITE V. S. F. O.; THEODORO R. Characterization of a coupled copper-water heat pipe with a Free Piston Stirling Engine. In**: BRAZILIAN CONGRESS OF THERMAL SCIENCES AND ENGINEERING**, 2020, Online conference. Proceedings […]. Rio de Janeiro: Associação Brasileira de Engenharia e Ciências Mecânicas, 2020. p. 1-10.

[11] SANTOS A.C.; GUIMARÃES L. N. F.; LEITE V. S. F. O.; THEODORO R. Effect of the inclination angle on the performance of 100 and 30 mesh screen copper water heat pipes for application in a Stirling engine. In: **INTERNATIONAL CONGRESS OF MECHANICAL ENGINEERING**, 2021, online conference. Proceedings […]. Rio de Janeiro: Associação Brasileira de Engenharia e Ciências Mecânicas, 2021. p. 1-10.