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Problems of sodium using in pulsating heat pipe made from fused silica

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Abstract. You Heat pipe is a high efficiency heat transfer element, depends on the evaporation, condensation and circulation of inside working fluid. The working fluid of a high temperature pulsating heat pipe is generally alkali metals, and sodium heat pipe can operate in range of 500-1100 ℃. In order to investigate terminal velocity of working fluid, the glass pulsating heat pipe was produced for experimental purposes. The experiment was carried out, in order to simulate real operating conditions in range of 500-1100 ℃. Sudden boiling of liquid sodium (b.p. = 883 ℃ at 1 atm) inside the all quartz-made heat pipe results in high-temperature reaction of sodium vapour with the inner wall surface. The reaction became more aggressive with increasing vapour temperature and resulted in heat pipe explosion. The evaluation of damage character is analysed in this paper.

1 Introduction

Worldwide production of aluminium consumes about 3.5% of the total global electric power. During the aluminium production, 50% of the supplied energy is consumed by the chemical process, and 50% of the supplied energy is lost in form of heat. Heat losses are necessary to maintain a frozen side ledge to protect the side walls, so extra heat has to be wasted. As the energy costs account for 40% of the total production costs, it is clear that the heat recovery optimization offers a significant economical end environmental potential in the industry. In order to increase the energy efficiency of the process, it is necessary to significantly lower the heat losses dissipated by the furnace's external surface. Extracting the waste heat (capturing it in a heat transfer fluid) also requires adapted heat-exchanger designs. The technology based on the use of heat pipes, has been developed for utilization energy from the waste heat produced in the electrolytic process. The heat recovery system can control the ledge thickness and thermal energy can be utilized by other energy demanding processes and increase the aluminium production by 20% and still achieve thermal balance. With heat recovery system, 10-12% of the total energy consumption for the furnace can be recovered [1].

Heat pipe is very good thermal conductor and has the ability to transfer heat hundred times more than copper. The high and super high temperature heat pipes have emerged as interesting alternatives to conventional heat transfer technologies and have wide applications in space thermal control, solar storage power plant, nuclear thermal control, the constant industry stoves etc.[2].

The aim of the project was to develop an innovative heat to electricity converter without any moving parts, placed on the pulsating heat pipe (PHP). Device can generate electric power by means of the interaction of a moving fluid and a magnetic field. One of the tasks was to measure the velocity of working fluid in the glass heat pipe and then analyse the efficiency of converter.

2 Experimental measurements

The experimental setup for the energy utilization of waste heat consists of PHP, which is a two phase heat transfer device with outstanding effective thermal conductivity. It is a vacuum tight device consisting of an envelope (here made of quartz glass) and flowing fluid (liquid sodium), which transfers heat under isothermal conditions at vaporization.

Sodium is a very reactive element because of his electron configuration in the valence shell where it is a single electron. That it readily donates, creating a positively charged ion - the Na+ cation. To achieve nonreactive condition, the pulsating heat pipe was cleaned with isopropyl alcohol 3 times. Subsequently, the pipe was heated up to 120°C, evacuated with turbomolecular pump and filled with argon (Purity 6). This procedure was repeated 3 times, in order to eliminate concentration of oxygen and impurities.

After cleaning the system and filled with argon, the pulsating heat pipe was evacuated for seven days and then filled with cleaned sodium. In order to prevent the

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solidification of Na in the system, the entire heat pipe and also filling system were heated up to 120°C.

The evacuation was stopped in this phase, valve to the vacuum pump was closed and liquid sodium has been released through the filling system to the heat pipe. After filling of PHP, the silicon tube was closed by two tubing clamps. The experimental setup is shown on Fig. 1.

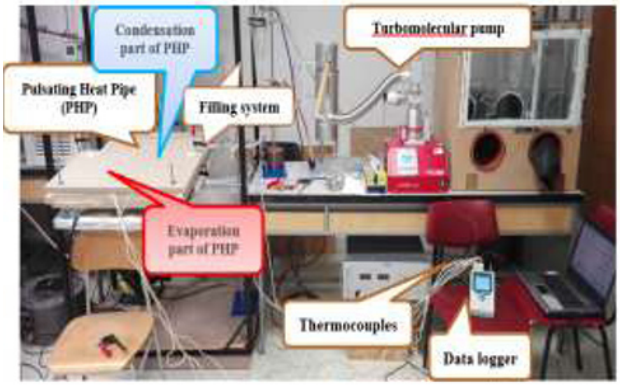

Figure 1. Experimental setup

3 Evaluation of the failure reason

Sodium was used in experimental apparatus as transport medium because of its convenient physical properties (conductivity, low melting and evaporating temperature, low weight etc.). It was supposed that its high chemical aggressiveness will be restricted by high vacuum and keeping of constant working temperature [3]. But in two hours the experimental device exploded in the evaporation part. It can be seen (Fig. 2.) that character of compounds inside of PHP is in various parts different and is changed with temperature. The temperature profiles of the PHP are presented in Fig. 3 and 4. To identified composition of black substance on the pipe walls in the part of explosion (evaporation part of black colour) microscopic and XPS methods were applied, in order to analyse the factors causing the explosion of heat pipe.

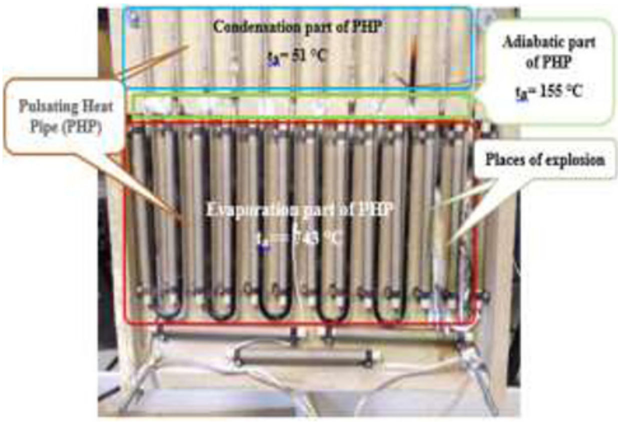

Figure 2. Detail of damaged pulsating heat pipe

The XPS analysis shows the presence of the pure carbon in high concentration on the quartz pipe wall (Tab. 1).

Table 1. Composition of the black products adherent on the pipe walls

Element	Weight %	Atomic %
Carbon C	81.11	87.79
Oxygen O	9.9	8.04
Silicone Si	9.0	4.17

According to the analysis, the explosion was caused by the high temperature followed devitrification of the fused silica pipe by sodium [4] and heterogeneity of reactions inside of experimental system. Increasing of diffusion through the weakening walls and created failures were followed by chemical reaction of sodium with components of ambient atmosphere.

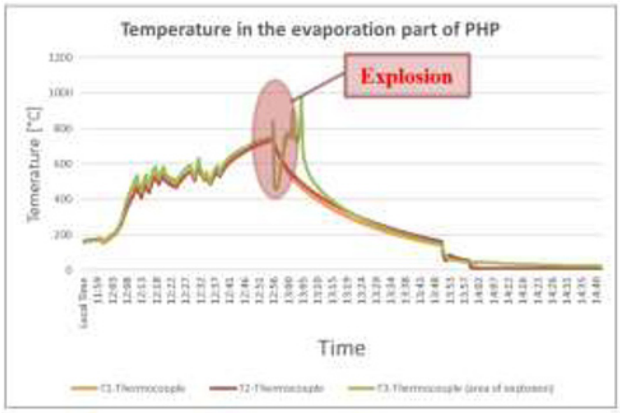

Figure 3. Profile of temperature in the evaporation of pulsating heat pipe

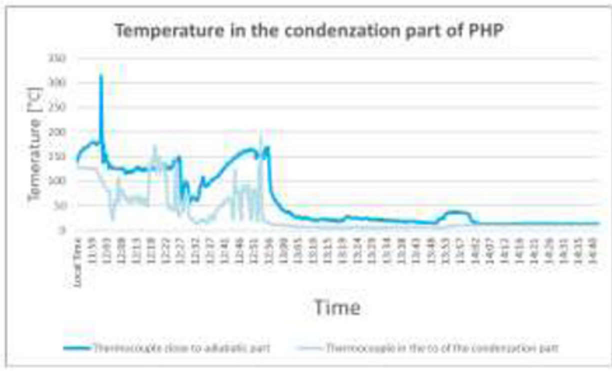

Figure 4. Profile of temperature in the condensation part of pulsating heat pipe

4 Summary and discussion

By thermal influence, the devitrified areas tend to weaken the PHP mechanically and change its properties and compatibility. Also, these devitrified areas which provide grain boundaries in the previously amorphous structure encourage diffusion by forming easy diffusion paths for environmental impurities to molten sodium [5]. The mechanism of devitrification as enhanced by sodium involves diffusion of sodium into the fused quartz. The sodium is thought to diffuse quickly through the open structure of the silica via strings of interconnected interstices [6]. The sodium sets up nucleation sites for crystallization. One can view a piece of a fractured glass pipe from a wet oxidation that has failed due to devitrification. It will be observed that the heavily devitrified region is inside of the pipe wall too. This is because water acts to greatly enhance the rate of devitrification [7].

The character of the pipe walls damage at various temperatures in the experimental apparatus as shown in Fig. 5 and is in the agreement with the published knowledge. As it can be seen the great differences are observed in intensity and nature of silica glass damage of the PHP. The Fig. 5a shows the expressive traces of surface etching as well as cracks caused by interaction of sodium with fused glass at high temperature and interactions with environment in the evaporation part. In the transit part, the temperature rapidly dropped and destruction of pipe was lower as it is presented in Fig. 5b where only slight attack of pipe surface was noticed. It is interesting that in the condensation part in spite of lower temperature the pipe surface damage was more intensive (Fig. 5c) which is probably due to different ambient conditions. In Fig. 5d, the original pipe surface is shown for comparison of various characters and intensity of attack in the heat pipe.

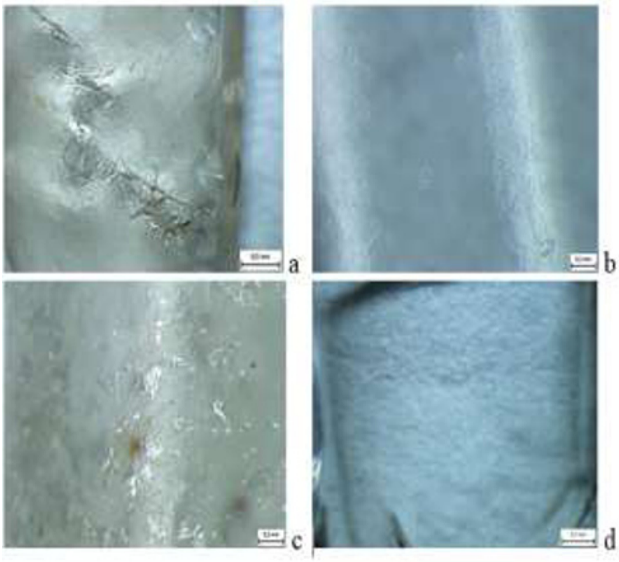

Figure 5. Character of fuse quartz pipe walls damage a) evaporation zone, b) transit zone, c) condensation zone, d) original pipe

The intensity of wall damage was affected by temperature very strong. The dimensions and quantity of disturb localities subjected reaction intensity as well as various characters of reaction products. Reactions of infused reactants with boiling sodium are very inhomogeneous as it can be seen from character of products especially in evaporation part (Fig. 6).

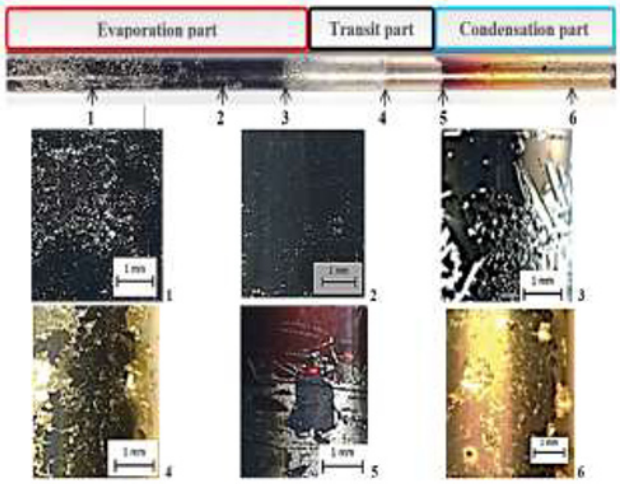

Figure 6. Character of the products in the fused glass pipe in different parts of experimental equipment differing in temperature

This fact made possibility to evoke different tensions and chemical composition in various localities of evaporation part and consequent explosion of the quartz pipe. The differences in reaction products are identified in transit and condensation parts. The variabilities of reactions become evident by various colour of reaction products [8].

This can be affected by different ambient and diffusion conditions in the condensation part from atmosphere since the transit part of the PHP is insulated and fixed in a solid holder.

5 Conclusions

• The visualization process of the liquid sodium flow in the PHP is not possible to investigate in fused silica tubes because the sodium can penetrate inside of pipe in very short time at temperature higher than 700°C and destroy it.
• The destruction of the fused silica pipe is influenced by penetration of sodium to pipe walls as well as with reaction compounds penetrated inside to tube through created defects.
• As the result can be concluded, that visualization in this form is not applicable and using of the fused silica pipe is possible only in the condensation part.

Acknowledgement

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References

1. R. Nosek, et al., *Utilization of waste heat from aluminium melting furnace* (AIP Conference Proceedings, Volume **1917**, PIM, 2017)

2. Q.Wei, *Progress Works of High and super high temperature heat pipes* (Developments in Heat Transfer, Chapter 25, ISBN 978-953-307-569-3, pp. 504-512, 2011)
3. J.Krätsmár-Šmogrovič et al., *Všeobecná a anorganická chémia (in Slovak)* (II. edition, Osveta ISBN 8080632458, 2007)
4. K. B. Richter, *Prevention of sodium diffusion through furnace tube quartz* (Lehigh University-Lehigh Preserve Theses and Dissertations, 1984)
5. P.F. Schmidt, *Contamination-Free High Temperature Treatment of Silicon or other materials* (J. Electrochem. Soc.,Vol. **130**, 1983)
6. S. J. Rothman, *Diffusion of Alkali Ions in Vitreous* (Silica,11 J. Am. Ceram. Soc.T, Vol. **65**, 1982)
7. W. Heng-yu and W. Jia-fan, *A study on the devitrification of silica glass tube the diffusion furnace* (Silicate Journal, Vol. **9**, 1981)
8. K. D. Kihm, D. M. Pratt and A. D. Swanson, *Condensation of sodium and high-temperature reaction with quartz pore inner surface* (J. Heat Transfer 131(8), 2009)