ANALYSIS OF THERMAL ENERGY STORAGE OPTIMIZATION OF THERMAL INSULATION MATERIAL AND THERMAL INSULATION STRUCTURE OF STEAM PIPELINE

Yipu WANG[1*],Zhengtao TU[2],Linyang YUAN[3]

[*1]School of Power and Mechanical Engineering, Wuhan University, Wuhan, China

[2]School of Construction Engineering, Jiangxi Normal University of Science and Technology, Nanchang, China

[3]School of Computer Science, Wuhan University, Wuhan, China

[*] Corresponding author; E-mail: yipuwang_whu@163.com

Abstract*: In order to improve the steam pipe insulation material joints, waterproof, and other shortcomings, and provide a good design scheme for the insulation structure optimization, a gel heat preservation material was prepared through hydration hardening theory. Firstly, the preparation of thermal insulation material for steam pipe and the optimal design of thermal insulation structure was introduced. Then the performance of the insulation material of the steam pipe was evaluated. Finally, the stability and energy benefit of the thermal insulation structure were evaluated. The results show that the new gel thermal insulation material prepared in this research has good thermal insulation effect and good waterproof performance. In the stability evaluation of the thermal insulation structure of the steam pipe, it can be concluded that hard thermal insulation materials should be selected in the selection of thermal insulation materials. Its insulation effect is better than soft insulation material. In the thermal energy storage optimization of the thermal insulation structure, when the inner layer of the thermal insulation structure adopts 10mm aerogel and the outer layer adopts 50mm gel thermal insulation material, it is the optimal thermal insulation structure. The study has a good guiding effect on the economic benefit of steam pipe insulation structure.*

Key words*: Steam line; Insulation material; Thermal insulation structure; Energy storage optimization*

1. Introduction

Energy is the most direct wealth endowed to human beings by the earth. After the age of steam, energy has provided the most basic life guarantee for human beings. Energy has always been the focus of global human concern. From national development strategies to people's lives, every country has an inseparable relationship with energy [1]. According to relevant statistics, oil, coal, and natural gas have always ranked among the top three in energy consumption.These three kinds of energy are closely related to human's daily life and are the main source of human's primary energy [2]. People obtain steam through coal, oil and other raw materials, and use steam to carry out various industrial production activities and People's Daily life. These vapors are mainly transported by steam pipelines [3]. Therefore, in order to improve the utilization rate of coal, oil and other raw materials, it is needed to find better energy-saving technology.

At present, the most commonly used energy saving technology is thermal insulation technology. The application of this technology in the pipelines producing steam transportation of coal, oil and other raw materials can reduce the consumption of steam heat energy in the transmission process and improve the economic benefits of steam [4]. However, according to the current research, the existing thermal insulation technology makes the average loss of heat in the pipeline transportation of steam between 5% and 8%, and to achieve this consumption must be set up in the steam transmission process of small heat source points. This allows for less loss of heat transport over longer distances, and the transport radius of the steam pipe can be greater than 7km. Although it is possible to provide good demand for steam power by building small heat source points in the middle of the process, there are also many problems [5]. All these small heat sources adopt small boilers, which have many disadvantages, such as more number, lower efficiency, greater pollution and smaller load, and their disadvantages far outweigh the benefits, causing great damage to the surrounding environment [6]. As China's 13th five-year development plan clearly points out, the radius of steam pipeline transportation needs to be increased to form concentrated heat supply. In response to good environmental development strategies, small boilers need to be phased out [7,8]. At present, there are many thermal insulation materials, but the traditional thermal insulation materials have the disadvantages of too thick insulation layer, too many joints and poor waterproof. Therefore, in the process of replacing boiler with thermal insulation material, it is necessary to evaluate the performance of thermal insulation material selection and provide corresponding calculation analysis for the optimization of thermal insulation structure [9].

To sum up, in order to solve the problem of economic effect of steam pipe in China, the gel method is used to prepare heat preservation materials for steam pipe. Through the optimal design of the thermal insulation structure, the performance of the thermal insulation material of the steam pipeline is evaluated. It is hoped to provide a good idea for material selection and energy storage design of thermal steam transmission pipeline in China.

2. Methodology

2.1. Preparation of thermal insulation material for steam pipe

Based on the hydration and hardening mechanism of gelatinized thermal insulation material, the thermal insulation material with high strength, high thermal insulation and good water resistance was prepared. The preparation process of thermal insulation material in this paper mainly includes three stages, which are: the hydration and dissolution stage of solid powder and activator, the gelation stage of thermal insulation material for gas injection pipeline, and the strength hardening stage of thermal insulation material for gas injection pipeline.

During the hydration phase, the solid powder used to prepare the gel insulation material is fully mixed with water. Since when CaO and Al_2O_3 in the solid powder are dissolved in water, hydroxide ions combine with them to form gels such as $Fe(OH)_3$, $Ca(OH)_2$ and Al_2O_3. In order to prevent the gel from solidifying too quickly, retarders and early-strength agents should be added to the reaction system during the hydration reaction of solid powders. Due to the complex hydration reaction of the activator, it is divided into two processes: infiltration and dissolution. When the activator is mixed with the cementitious insulation material, a series of complex processes of crystallization will occur [10]. The macroscopic effect of hydration reaction of activator can be measured by calorimetry, as shown in Fig. 1.

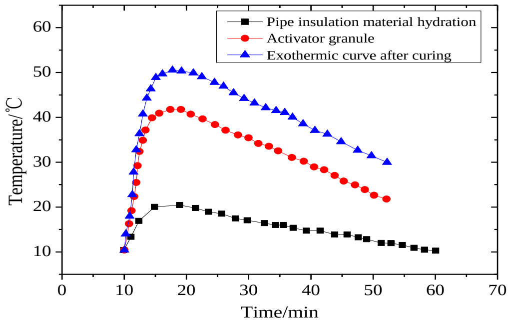

Figure. 1 Hydration exothermic curve of cementitious insulation material

The hydration saturation period of the activator is the same as that of the gel insulation material, but the activator contains more $Fe(OH)_3$ gel, $Ca(OH)_2$ gel and Al_2O_3 gel. The activator of gel insulation material contains a large amount of water, which is in the ionic state. When in the solution state, it has the good fluidity, and also ensures the thermal insulation construction simple and is easy to operate.

During the gelatinization period, the activator and the gel insulation material were mixed and stirred with water. After the water was saturated, the hydration reaction of the material reached its peak. The original equilibrium in the water is destroyed, and the ionic charges and structures rearrange. The water system generates a large amount of heat, which is rearranged in CA-O, O-H, FE-O, SI-O and AL-O bonds, resulting in increased bond energy and more stable energy [11].

During the strength hardening period, the pipe insulation material meets water and condenses. Branched crystalline ferric aluminum sulfate is the hydration product of this reaction. Calcium aluminate ferric sulfate trtringite has a good water absorption and can inhale and convert water into crystalline water. The main process at this time is crystallization.

2.2. Optimum design of insulation structure

2.2.1 Optimal calculation of steam pipe insulation

The design of steam pipelines should follow the three principles of economy, heat dissipation and external surface temperature. Under the guidance of the three principles, requirements of less heat loss, energy saving and process should be met [12,13].

The calculation principle of the optimal economic thickness is the influence of pipe diameter and insulation material on the total annual working cost. The resulting insulation thickness at the lowest annual total cost is "optimal economic thickness", as shown in Fig. 2.

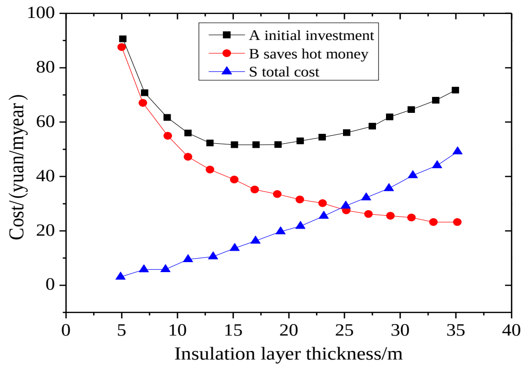

Figure. 2 Schematic diagram of steam pipe insulation (A- sum of annual apportionment cost of insulation project investment and annual maintenance cost; B- annual heat dissipation loss expenses after thermal insulation; S- total annual work expenses)

According to Fig. 2, value A increases with the increase of insulation layer thickness, value B decreases with the increase of insulation layer thickness, and value S is A minimum value point with the change of insulation layer thickness. The insulation thickness taken at this point is the economic thickness of insulation layer.

2.2.2 The mathematical model of steam pipe insulation economy

The purpose of optimizing the thermal insulation of steam pipeline is to make the thermal insulation economical, and to minimize the annual cost of heat loss and the annual investment cost of thermal insulation structure.

The annual cost of heat loss is expressed as:

$$S_r = \Phi \times t \times M_h \times L \tag{1}$$

In the equation, Φ represents heat flow; trepresents the working time of the insulation pipe; M_h is the unit price of heat; L represents the length of the pipe.

It is assumed that the pipeline working time and heat unit price in Eq. (1) are known, so the heat flow calculation formula of multi-layer insulation material can be expressed as:

$$\frac{d}{dr}(r\frac{dt}{dr}) = 0 \tag{2}$$

Boundary condition expressions can be divided into two cases: (1) when $r=r_1$, $t=t_1$; (2) when $r=r_2$, $t=t_2$.

By integrating Eq. (2), Eq. (3) of Eq. (2) can be reached:

$$t = c_1 \ln r + c_2 \tag{3}$$

When Eq. (3) is changed, when the values of c_1 and c_2 are determined, the solvable is:

$$c_1 = \frac{t_2 - t_1}{\ln(r_2/r_1)} \tag{4}$$

$$c_2 = t_1 - \ln r \frac{t_2 - t_1}{\ln(r_2/r_1)} \tag{5}$$

$$t_2 = t_1 + \frac{t_2 - t_1}{\ln(r_2/r_1)} \ln(r/r_1) \tag{6}$$

According to the above calculation process, the temperature distribution in the cylinder wall of the steam pipe is a logarithmic curve. By taking the derivative of Eq. (6), it can be deduced that:

$$\frac{dt}{dr}=\frac{1}{r}\frac{t_2-t_1}{\ln(r_2/r_1)} \tag{7}$$

According to Eq. (7), in a pipe, the radius is constant and the heat flux is inversely proportional to the radius, but the heat is constant and does not change.

Both sides of Eq. (7) are multiplied by $2\pi R_1$, and it is gotten:

$$\Phi=2\pi rlq=\frac{2\pi rl(t_1-t_2)}{\ln(r_1-r_2)} \tag{8}$$

According to the concept of thermal resistance, the thermal resistance of the whole pipeline can be expressed as:

$$R=\frac{\Delta t}{\Phi}=\frac{\ln(d_2/d_1)}{2\pi\lambda l} \tag{9}$$

According to the superposition principle of heat resistance in series, it can be deduced that the heat conduction of multi-layer pipeline can be expressed as:

$$\Phi=\frac{2\pi l(t_1-t_2)}{\ln(d_1/d_2)/\lambda_1+\ln(d_3/d_2)/\lambda_2+\ln(d_4/d_3)/\lambda_3} \tag{10}$$

It is supposed that the heat loss of convective heat transfer between the outer wall of the pipeline and the environment is Φ_1 and Φ_2, according to Newton's cooling theorem:

$$\Phi_1=2\pi r_1 l h_1(t-t_2) \tag{11}$$

$$\Phi_2=2\pi r_4 l h_2(t_4-T) \tag{12}$$

Since the heat flow in the pipeline is a steady-state process and the heat transfer area is certain, there are:

$$\Phi=\Phi_1=\Phi_2 \tag{13}$$

From Eq. (10) to Eq. (13), it can be deduced that the heat loss of steam in the pipeline is:

$$\Phi=\frac{2\pi l(t-T)}{\frac{1}{r_1h_1}+\ln(d_2/d_1)\Big/\lambda_1+\ln(d_3/d_2)/\lambda_2+\ln(d_4/d_3)\Big/\lambda_3+\frac{1}{r_4h_2}} \tag{14}$$

$$t=\frac{(t-T)}{(\frac{1}{r_1h_1}+\ln(d_2/d_1)\Big/\lambda_1+\ln(d_3/d_2)/\lambda_2+\ln(d_4/d_3)\Big/\lambda_3+\frac{1}{r_4h_2})\times h_2}+t \tag{15}$$

3. Results

3.1. Performance evaluation of steam pipe insulation materials

In this research, the thermal insulation properties of thermal insulation materials are comprehensively evaluated. The thermal conductivity, compressive properties, tensile strength, hot-wire shrinkage and thermal shock resistance are measured. In order to prove the superiority of the gelatinized thermal insulation material developed in this paper, it is compared with aerogel, titanium ceramics and microporous calcium silicate.

Table.1 Compared with other three thermal insulation materials

Performance evaluation	Aerogel	Microporous calcium silicate	Titanium ceramic	Cementitious insulation material
Tensile Strength /kPa	178	341	476	305
Compressive strength /kPa	1316	1908	2245	1934
Line shrinkage /%	1.84	1.76	1.34	2.1
Thermal conductivity /W • m^{-2} • K^{-1}	0.0327	0.042	0.037	0.040
Thermal shock resistance /%	10.4	1.1	1.34	2.2
Volume weight /kg/m^3	206	225	326	227
Maximum service temperature /°C	1200	1000	1000	1000
Texture and characteristics	Soft and harmless	Hard and harmless	Hard and harmless	Hard and harmless

According to the results in Tab. 1, the thermal conductivity of the thermal insulation material developed in this research is 0.040w·m^{-2}·K^{-1} at 300°C, and as the temperature rises, the insulation material developed in this research has good stability performance.

3.2. Structural stability evaluation of thermal insulation material for steam pipeline

3.2.1 Relationship between thermal insulation structure of steam pipe and amplitude

After the comprehensive evaluation of the thermal conductivity, compressive properties, tensile strength, hot-wire shrinkage and thermal shock resistance of the thermal insulation material developed in this research, the stability of the thermal insulation material and other three materials were compared. Fig. 3 shows the relationship between heat flux and amplitude of four insulation materials. It can be concluded from the figure that, in the case of no environmental change, the insulation effect of the insulation material prepared in this paper is double-layer aluminum silicate material.

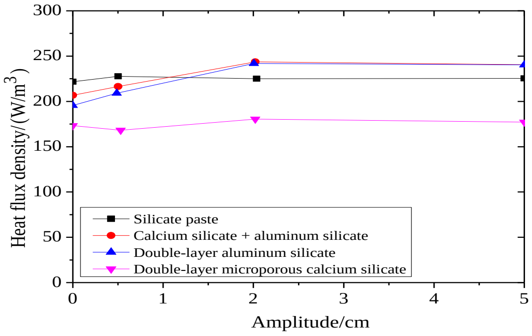

Figure. 3 The relationship diagram of heat flux and amplitude of four kinds of insulation materials

Fig. 4 shows the change curves of heat flux and vibration strength of four thermal insulation structures. When the external environment changes, the vibration intensity has the least impact on the structure of silicate paste and the insulation material prepared in this paper. The heat flux does not change too much with the change of vibration intensity. For the other two thermal insulation materials, with the increase of amplitude, the heat flux also tends to rise. When the vibration intensity reaches 20cm, the heat flux also reaches the maximum value, while the heat flux is kept at a relatively stable level. Therefore, for the vibration strength, the insulation materials prepared in this paper and silicate paste structure should be used in the selection of insulation layer materials.

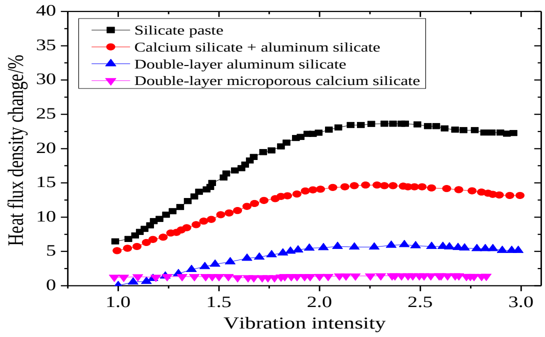

Figure. 4 The change curves of thermal flux and vibration intensity of four thermal insulation structures

3.2.2 Relationship between thermal insulation structure of steam pipe and impact force

Fig. 5 shows the relationship between the heat flux and the impact force of four insulation materials; Fig. 6 shows the relationship between the change rate of heat flux of four insulation materials and the impact force strength curve. In the event of changes in the external environment, the impact force received on the steam pipe according to the change rate of heat flux, the order of the insulation effect is: gel insulation material > silicate paste > double-layer fiber felt > calcium silicate + aluminum silicate composite insulation material. With the increase of the impact force, the heat flux of the four selected thermal insulation materials has changed and the heat flux increases. According to Fig. 5, in the case of relatively small impact force, its influence on the double-layer ten thousand pieces of thermal insulation structure and silicate paste thermal insulation structure is minimal. In the case of large impact force, the gel thermal insulation material prepared in this paper shows excellent performance. In addition, the performance of silicone paste is also very good, but the remaining two thermal insulation structure is inferior. Therefore, in terms of impact resistance, the thermal insulation material prepared in this paper has better performance under a larger impact.

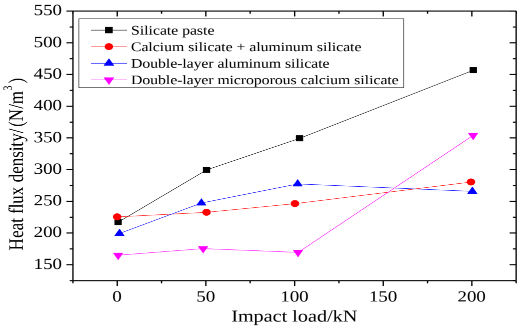

Figure. 5 The relationship between thermal flux and impact force of four thermal insulation materials

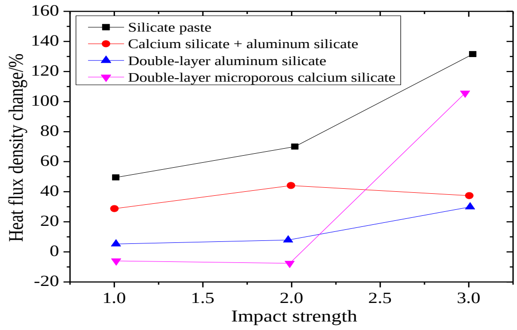

Figure. 6 The relationship between the change rate of heat flux and impact strength curve of four thermal insulation materials

3.3. Evaluation on energy saving benefit of thermal insulation structure storage

The energy saving of various insulation materials is compared. When the steam temperature is 350°C and the ambient temperature is 25°C, the internal streamline density of the steam pipeline is 200~300W/m. In this research, Q1 is 200W/m. The price of thermal insulation material is consistent with the market price, and the economics of different thermal insulation material structures are compared, as shown in Tab. 2.

Table. 2 Economic comparison of different thermal insulation structures

Insulation structure	Save cost/yuan per year	Insulation cost investment/yuan	Cost/yuan (km*a)$^{-1}$		
			Annual apportionment fee for thermal insulation materials	Cooling losses	Comprehensive costs
Double layer calcium silicate structure	159900	61886	6808.56	1913734	1920434
Aerogel + calcium silicate tile + complex acid structure	682000	292421	32157.24	1391870	1423757
Aerogel + spherical silicon + composite silicate structure	552340	305689	33628.81	1522353	1555761
Aerogel + double layer calcium silicate	801484	241698	26587.77	1272164	1298642
Aerogel + spherical silicon + ceramic fiber	584012	257803	28353.55	1489574	1518227

Aerogel + gel insulation material	888426	253479	27881.03	1185266	1213147
Aerogel + double ceramic fiber	741450	212150	23338.01	1332363	1355401
Aerogel + double aluminum silicate	757410	216936	23863.85	1316292	1340156

According to Tab. 3, aerogel + gel insulation material has the best comprehensive index in the insulation structure, with the lowest comprehensive cost. Therefore, aerogel + gel insulation material is the optimal combination of insulation structure. Considering the thickness of the pipe insulation layer, the difficulty of construction, and the stability of the insulation structure, the double thickness of the aerogel used for the insulation lining is 10mm, and the gel thickness of the external insulation material is 50mm, so 10mm aerogel +50mm gel insulation material should be selected.

4. Discussion

Through the performance test, it is found that the gel insulation material not only has good hydrophobicity and good tensile and compressive properties, but also has cheap raw materials, which is a kind of insulation material with good economic performance. The research results are the same as those in literature. According to literature, silicone hydrophobic agents are applied to the waterproof treatment of thermal insulation materials, such as waterproof perlite products, water-repellent microporous calcium silicate products, hydrophobic foam asbestos and waterproof aluminum silicate fiber products. It was also concluded that microporous calcium silicate products containing surface hydrophobicity were 93% hydrophobicity. At the same time, the structural stability of the insulation material is evaluated. It is concluded from the research that when the vibration intensity reached 20cm, the heat flux also reached the maximum value, and the change rate of heat flux also increased with the increase of the impact force. Therefore, it indicated that the structural selection of thermal insulation material for the steam pipeline had better performance. In order to ensure the stability of the thermal insulation structure, the double-layer thickness of aerogel used for thermal insulation lining is 10mm, and the gel thickness of external thermal insulation material is 50mm. The results of this study are highly consistent with the research in literature. According to literature, when the thickness of the insulation layer increases gradually, the thermal conductivity resistance of the insulation layer increases. However, as the outer surface area of the insulation layer also increases at the same time, the convection heat transfer resistance between the insulation layer and the environment decreases. Therefore, the increase of the insulation thickness may increase the heat dissipation loss of the pipeline. Therefore, there is a critical insulation thickness, only when the insulation thickness exceeds the critical insulation thickness, the use of insulation material is actually effective. Therefore, the research provides the best scheme for the optimization of the thermal insulation structure of steam pipeline, which can make the thermal insulation structure have economic benefits.

5. Conclusion

In terms of thermal energy storage optimization of thermal insulation structure, the optimal thermal insulation structure adopts 10mm aerogel for inner layer and 50mm gel for outer layer. The relationship between the thermal insulation structure of steam pipe and its stability is discussed, and it is concluded that the thermal insulation effect of hard thermal insulation material is better than that of soft thermal insulation material.

The research in this article has a good guiding significance to the current situation of heat supply distress in China. However, the microstructures of the prepared gel materials have not been studied in this research. It is hoped that subsequent studies can be extended in this aspect, which will make the research in this field more extensive and in-depth.

References

[1] NGonzález, R. E., *et al*., Review of Commercial Thermal Energy Storage in Concentrated Solar Power Plants: Steam Vs. Molten salts, *Renewable and sustainable energy reviews, 80* (2017), 4, pp. 133-148.

[2] Shaofei Wu. Construction of visual 3-d fabric reinforced composite thermal performance prediction system, Thermal Science, 23(2019), 5, pp.2857-2865.

[3] Wei, G., *et al*., Selection Principles And Thermophysical Properties of High Temperature Phase Change Materials for Thermal Energy Storage: A Review, *Renewable and Sustainable Energy Reviews*, *81* (2018), 14, pp. 1771-1786.

[4] Zhang, H., *et al*., Thermal energy storage: Recent Developments and Practical Aspects, *Progress in Energy and Combustion Science, 53* (2016), 12, pp. 1-40.

[5] Alva, G., *et al*., Thermal Energy Storage Materials And Systems for Solar Energy Applications, *Renewable and Sustainable Energy Reviews*, *68* (2017), 2, pp. 693-706.

[6] Li, Y., *et al*., District Heating and Cooling Optimization and Enhancement–Towards Integration of Renewables, Storage And Smart Grid. *Renewable and Sustainable Energy Reviews, 72* (2108), pp. 281-294.

[7] Shaofei Wu,Mingqing Wang,Yuntao Zou. Research on internet information mining based on agent algorithm, Future Generation Computer Systems, 86(2018), pp.598-602

[8] Ladekar, C. L., *et al*., Experimental Investigate for Optimization of Heat Pipe Performance in Latent Heat Thermal Energy Storage, *Materials Today: Proceedings, 4* (2017), 8, pp. 8149-8157.

[9] Navarro, L., *et al.*, Thermal Energy Storage In Building Integrated Thermal Systems: A Review. Part 1, Active Storage Systems. *Renewable Energy*, *88* (2016), pp. 526-547.

[10] Li, G., Zheng X., Thermal Energy Storage System Integration Forms For a Sustainable Future, *Renewable and Sustainable Energy Reviews*, *62* (2016), pp. 736-757.

[11] Mohamed, S. A., *et al*., A review on current status and challenges of inorganic phase change materials for thermal energy storage systems, *Renewable and Sustainable Energy Reviews*, *70* (2017), pp. 1072-1089.

[12] Alva, G., *et al.*, An overview of Thermal Energy Storage Systems, *Energy*, *144* (2018), pp. 341-378.

[13] Myers Jr, P. D., Goswami, D. Y., Thermal Energy Storage Using Chloride Salts and Their Eutectics, *Applied Thermal Engineering*, *109* (2016), pp. 889-900.