Research, Development and Industrial Application of Heat Pipe Technology*

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Abstract: This paper introduces some typical cases of industrial applications, which include the equipment for the waste heat recovery and the industrial process equipment. Carbon steel-water heat pipe technology, applied to air preheater and waste heat boiler, has been successfully used in many fields, such as waste heat recovery, energy conservation and environmental protection. Liquid metal high temperature heat pipe technology has been extensively employed in the process equipment; high temperature hot air generators and heat extractors, for example. Heat pipe technology also finds its use in chemical reactors including ammonia converters. The successful applications is based on the fundamental research of heat pipe technology, which includes the theoretical and experimental researches on the vapor-liquid two-phase flow and heat transfer inside the heat pipe, the heat transfer limits of heat pipes, the heat transfer enhancement with heat pipes, and researches on the material compatibility and life tests of heat pipes. The hi-efficient heat pipe heat & mass transfer equipment is going to play a more and more important role in various industrial fields.

Key words: heat pipe technology, carbon steel-water heat pipe, liquid metal heat pipe, waste heat recovery, industrial process, heat pipe reactor

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1 Introduction

As a highly-effective heat transfer element, heat pipes have been gradually recognized, and are playing a more and more important role in almost all industrial fields. After more than 20 years of efforts, China has successfully developed a series of heat pipe equipment such as heat pipe gas-gas exchangers, heat pipe steam generators (waste heat boilers), high temperature heat pipe (liquid metal heat pipe) steam generators, high temperature heat pipe hot air furnaces, and has made remarkable progresses in the fields of metallurgy, petrochemical, chemical, power and construction material industries[1] on the basis of experimental and theoretical investigations. In This paper introduces the research work carried out in the National Technology Research & Promotion Center for Heat Pipe (NTRPC-HP) for the purpose of the industrial applications of heat pipe technology, with the examples of researches and applications presented. Table 1 shows some applications of the heat pipe equipment in various industrial fields. The profound experimental researches on the heat pipe technology support its applications. These include the heat pipe waste heat recovery equipment for energy-saving and environmental protection; heat pipe air preheaters and heat pipe steam generators adopting carbon steel-water heat pipe technology, and the heat pipe industrial process equip-

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ment, such as highly-effective heat pipe exchangers, the high temperature heat pipe hot air furnaces and high temperature heat pipe heat extractors involving the use of liquid metal heat pipe technology, and the key industrial process equipment now being developed-high temperature and high pressure (480 ℃ and 32 MPa) heat pipe chemical reactors. All these demonstrate the broad prospects of application of heat pipe technology to industries.

Table 1 Application of the heat pipe equipment in various industrial processes /set (NTRPC-HP)

Industrial field	Heat pipe gas-gas exchanger	Heat pipe steam generator	Heat pipe gas-liquid exchanger	Separate type heat pipe exchanger	High temp. heat pipe exchanger
Petroleum, Chemical	119	36	10		3
Metallurgy	36	40	6	30	
Construction Material	20	26	8		4
Power	20	8	4		2
Sub-total	195	110	28	30	9
Total	372				

2 Some important features of application of heat pipe technology in industries[2]

The extensive applications of heat pipe technology in industries with great prospects are based on the essential features of the heat pipe. These features, when combined with specific technical processes, bring into full play of the superiority of the heat pipe technology and also solve the practical problems in industrial produc-tion in an efficient and economic way. This is the key for the application of heat pipe technology in industries.

The features include:

(1) The high heat conduction performance of heat pipes. The heat pipe is a heat-conducting element with high heat transfer performance. It transfers heat via evaporation and condensation of the working fluid in the fully-enclosed vacuum pipe, at a heat conductivity several times or even nearly ten thousand times better than that of good heat-conducting materials (copper, silver, etc.), hence the name "heat superconductor".

(2) The dual-wall heat exchange characteristics of the heat pipe are an important guarantee for the safe, reliable and long-term operation. With traditional one-wall heat-exchange equipment, the equipment should be stopped for repair even when only one heat exchange element is damaged. This is not the case with the heat pipe equipment. Even if there is damage to a single heat pipe in the equipment comprising heat pipe bundles, the two different types of heat exchange fluids will not be mixed, and therefore the overall heat exchange effect will not be affected.

(3) The heat flux exchange and self soot-blowing characteristics of heat pipe are important technical guarantee to prevent dew-point corrosion and dust clogging in industrial equipment. It has been proved that such accidents as deterioration of equipment efficiency or even forced outage due to clogging and dew-point corrosion of large power station boilers, various industrial waste heat boilers in high dust content environment and other heat exchange equipment in dusty environment can be prevented and avoided when they are replaced with heat pipe heat exchangers.

(4) Separate type heat pipe technology has made heat exchange possible at long distance where mixing is not allowed and where multiple heat sources (or heat sinks) are used, and can therefore successfully overcome the difficulty in heating the gas and air at the same uime for the blast-furnace flue gas in iron melting

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and metallurgical industries.

(5) The homogeneous temperature and heat shielding performance of heat pipes can solve such problems as non-homogeneous temperature distribution in a chemical reactor and reaction deviating from optimum reaction temperature, the overheating decomposition due to uneven pipe wall temperature in petroleum crackers and heat dissipation for the nuclear reactor vessel body.

(6) Liquid metal heat pipe technology has made high-temperature heat exchangers safer, more compact and more efficient. The use of liquid metal heat pipes and reduction in material prices will make it possible to realize the continuous heat extraction in super high-temperature reaction equipment, such as continuous gas production in the coal gasification, and new type heat pipe steam generators in nuclear power plants.

3 Industrial applications of carbon steel-water heat pipe technology

On the basis of theoretical research, experimental study by simulating actual working conditions is a necessary step in realizing the industrial applications of heat pipe technology. With the issue of carbon steel-water heat pipe compatibility being solved, the cost of heat pipe equipment has greatly dropped. This, plus a number of superior properties of heat pipe technology, has enabled the extensive application of carbon steel-water heat pipe heat exchangers in industries. At present, heat pipe waste heat recovery equipment for energy-saving and environmental protection, such as heat pipe air preheater and heat pipe steam generator on the basis of the carbon steel-water heat pipe technology have become mature, and have found wide application in petroleum, chemical, metallurgical, power and building material industries.

3.1 Research and industrial application of carbon steel-water heat pipe steam generator

In-depth studies have been made on the heat transfer performance of carbon steel-water heat pipes and its limit of heat transfer by many research fellows of heat pipe technology [4, 5]. To realize industrial application and ensure efficient, safe and reliable operation of the designed heat pipe equipment in the industrial applications, such issues for the carbon steel-water heat pipe as maximum heat transfer capacity, maximum acceptiable temperature, enhanced internal boiling heat transfer to eliminate local overheating and service life must be solved. Therefore, a series of researches have been conducted in laboratories. And on this basis, heat pipe steam generators for application in high-temperature and highly dusty conditions have been successfully developed.

3.1.1 Maximum heat transfer capacity of carbon steel-water heat pipe

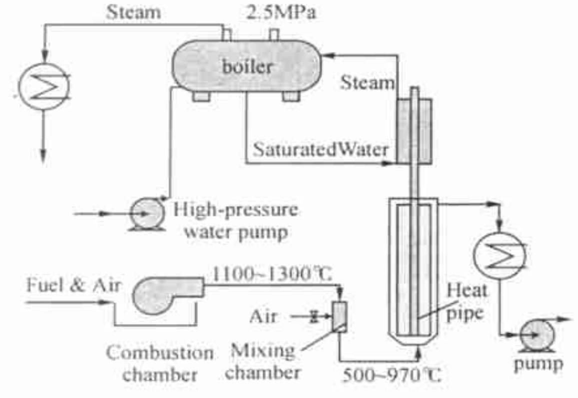

Fig. 1 Schematic of test system for the sigle heat pipe performance

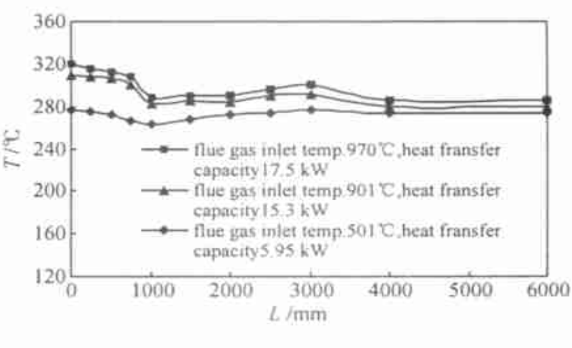

Fig. 2 Wall temperature distribution of heat pipe

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Fig. 1 is a test bench for single heat pipe performance simulating the condition that flue gas sweeps the heat pipe longitudinally[6], and the following researches have been conducted on the test system:

(1) Max. heat transfer capacity of a single heat pipe under testing conditions.

(2) Variation in wall temperature of the heat pipe under changing conditions.

(3) Verifying the correctness of theoretical calculation value.

In Fig. 2, the three curves represent the temperature distribution on the outer wall of the heat pipe and the maximum transferred power under three typical testing temperatures. The maximum transfer power measured is far below the theoretical value and values obtained in limit tests. Therefore the heat pipe is still safe when it is operating under the condition of maximum flue gas temperature of 700 ℃.

3.1.2 Study on enhanced boiling heat transfer in carbon steel-water heat pipes[7,8]

The carbon steel-water heat pipe has demonstrated great superiority as a heat transfer element of heat-exchange equipment, but there are still some problems in the actual application, such as entrainment limitation, serious unstable fluctuation of wall temperature, narrow applicable temperature range, etc. Therefore, to enhance its internal performance and widen its application, temperature is still one of the imperative technical issues to be solved in the promotion of heat pipe technology.

Inserting a coaxial perforated pipe (referred to as isocon in this paper) in the heat pipe is one of the effective and feasible methods to enhance its internal heat transfer. It converts the liquid pool boiling in the evaporating section into liquid boiling in narrow slots, and separates the vapor rising route in the evaporating section from the reflux condensed liquid, to reduce the interaction between vapor and liquid, while not affecting the normal evaporation and condensation. The main mechanism of an isocon to enhance the boiling heat exchange is to expand the covering area of the liquid film and to increase the disturbance of liquid around the bubbles.

The testing apparatus is shown in Fig. 3. The testing pipe is a carbon steel-water thermosyphon, ≊34 × 8 and 3000 mm in length, including an evaporating section of 1600 mm and a condensing section of 900 mm. The evaporating section is heated in a high-power silicon-carbon rod heating oven, and in the condensing section, water in the jacket can remove the heat. On the wall of the heat pipe, 15 pairs of thermocouples are fixed by spot welding for temperature measurement, and the steam temperature in the pipe is measured by a thermocouple in the center pipe. The isocons used are sized as ≊27 × 3, ≊25 × 1 and ≊22 × 1, with a porosity ε respectively at 3%, 16% and 33%. The testing study results are as follows:

(1) The structural dimensions of the isocon have a large bearing on the boiling heat transfer coefficient. Within a certain range, the higher the porosity is, the better heat transfer effect, and within the range permitted by engineering manufacture, the smaller the pipe clearance and thinner liquid film are, the better the heat transfer effect;

(2) The optimum isocon structure: the pipe clearance is about 4.5 mm with a porosity of about 33%. With the best isocon, under the same power transfer conditions, the steam temperature in the heat pipe is reduced by 15~30 ℃, and the internal heat transfer coefficient in the heat pipe is increased remarkably,

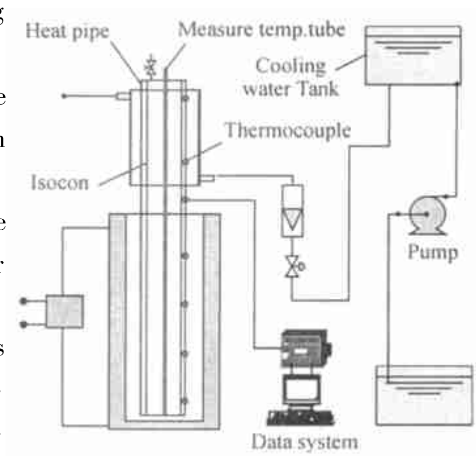

Fig. 3　Heat pipe power-test apparatus

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for about 2~ 3 times.

(3) The dimensionless number formula for enhanced boiling heat transfer of isocon obtained by performing multi-element linear least square regression analysis on 330 testing points is as follows:

$$Nu = 199.5 M_b^{0.315} \varphi^{-1.23} \varepsilon^{0.08} Pr^{0.009} (p/p_a)^{0.22}$$

Testing range: the characteristic criteria parameter of micro-layer liquid film $M_b = 2\times 10^{-5} \sim 4.67\times 10^{-4}$, the geometric characteristic criteria parameter of isocon $\varphi = 0.42 \sim 0.46$, porosity $\varepsilon = 3\% \sim 33\%$, and the ratio of working pressure to ambient pressure in the thermosyphon $p/p_a = 1.3 \sim 15.5$; $Pr = 0.9 \sim 1.46$.

3.1.3 Steam generator for high-temperature and high-dust content gases (waste heat boilers)

The reliability of steam generators for high-temperature and high-dust content gases (waste heat boilers) has always been a highlighted issue in chemical industry as well as in other industries. The most typical of this type of equipment is the waste heat boiler for the high-temperature SO_2 gas after the fluidized-bed roasting in the sulfuric acid industry. A 125 000 t/a sulfuric acid plant produces SO_2 gas at 277 744 Nm^3/hr, at an inlet temperature of 950 ℃, with a dust content of about 250 g/m^3 and a dew point temperature of 192~ 210 ℃. The operation parameters are shown in Table 2. The best features of heat pipe type steam generators are compact structure, small volume, light weight and high safety and reliability. Its mass is only 1/3~ 1/5 of that of an ordinary tube waste heat boiler and its overall dimensions only 1/2~ 1/3 of the latter. The pressure loss after the flue gas passes the waste heat boiler is normally 20~ 60 Pa, and therefore the power consumption of the ID pump is also quite low. Damage of a heat pipe element will not affect the circulation in the steam system, and it is not necessary to shut down the system for repair. Therefore, safety and reliability of the system have been greatly raised. The heat pipe steam generator used for this process was put into operation successfully in one trial in November 1996 on the basis of the experimental study. The site conditions are as shown in Fig. 4. It has been running up to now without any maintenance and repair. This fully indicates the operation reliability of a heat pipe steam generator under severe conditions.

Table 2 Operation parameters of heat pipe steam generator

	Cold side Water, steam	Hot side SO_2 gas
Flow rate	9.5 T/h	277 744 Nm^3/hr
Inlet temp. / ℃	104	950~ 970
Outlet temp. / ℃	224	355
Pressure/ MPa	2.5	Micro pressure

3.2 Heat pipe air preheaters

3.2.1 Investigation on heat pipe gas-gas heat exchangers

The research results on gravity type heat pipe heat exchangers and on the internal and external heat transfer coefficient of the heat pipes were published as early as in 1986[9].

Investigations were conducted on heat pipe gas-gas heat exchangers of 20 different structure types of 26~ 32 mm in diameter and 1.2~ 2 m in length under 300 different operation conditions. Fig. 5 shows the photo of the testing apparatus. This testing system permits performance tests on heat pipe heat exchangers at any tilting angle between 0~ 90 degrees. The Investigation results are. Correlated formula for heat transfer coefficient of integral heat pipe heat exchang-

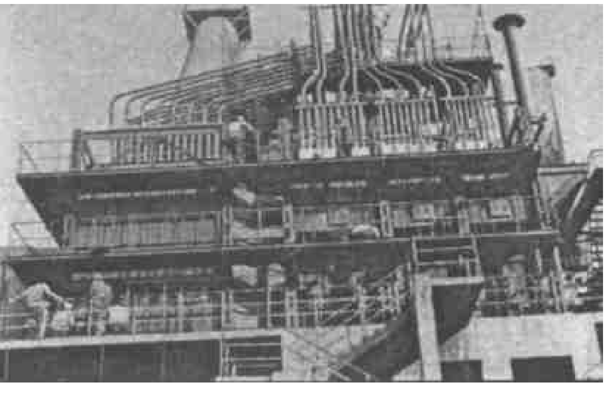

Fig. 4 Heat pipe steam generator for sulfuric production

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ers:

$$Nu = 0.01334 Re^{0.6249} Pr^{1/3} \left(\frac{Pr_w}{Pr}\right)^{0.25} \left(\frac{S_t}{d_0}\right)^{0.1999} \left(\frac{S_l}{S_t}\right)^{0.2093} \left(\frac{t_f}{h_f}\right)^{0.2470} \left(\frac{\delta_f}{t_f}\right)^{0.1365}$$

The pressure drop across the heat exchanger:

$$\Delta p = f \frac{L \cdot G_{max}^2}{\rho g d_{ev}}$$

$$f = 0.456 Re^{-0.2803} \left(\frac{\mu_w}{\mu}\right)^{0.14} \left(\frac{S_t}{d_o}\right)^{2.135} \left(\frac{S_l}{S_t}\right)^{-0.6469} \left(\frac{t_r}{h_r}\right)^{0.8191}$$

3.2.2 Heat pipe air preheaters

A typical heat pipe air preheaters is shown in Fig. 6. Its best features are simple structure, high heat transfer efficiency and convenient adjustment of heat exchange area ratio of the cold side to hot side, thereby effectively avoiding acid and dew point corrosion. Table 3 gives the main parameters of a large heat pipe air preheater used in the primary reformer of a large fertilizer plant[12]. The practical operation results show that the heat recovered by the heat pipe heat exchanger proper is equivalent to about 1 ton of diesel oil per hour, with apparent economic efficiency, and a demonstrative role in the energy-saving transformation for large fertilizer plants.

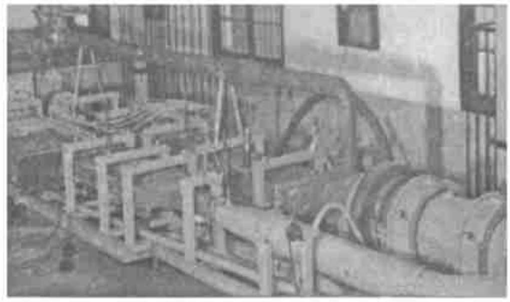

Fig. 5 Photo of the performance test system of a heat pipe gas-gas heat exchanger

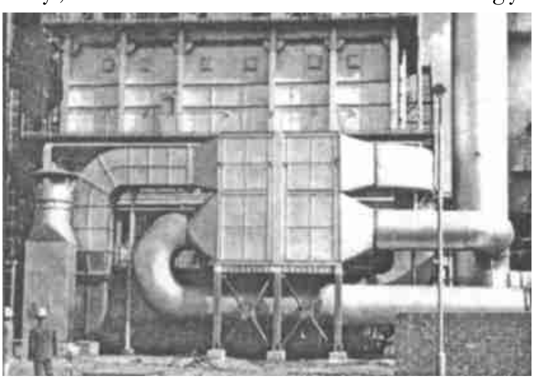

Fig. 6 Photo of Heat pipe gas-gas heat exchanger

Table 3 Parameters of heat pipe air preheater

Pipe size / mm	≈ 51× 4.5, L = 6 000, 1 914 pieces	
Heat exchanger size	Height 6.4 m, Length 2.4 m, Inlet width 13.7m, Outlet width 10.37m	
	Flue gas	Air
Flow rate / (Nm³/hr)	238 000	195 860
Inlet temp. / ℃	297.7	54.8
Outlet temp. / ℃	171.2	228.7
Pressure drop / Pa	580	280
Heat recovery / kW	43.1 Gj/h (11970kW)	

3.3 Design and standards for heat pipe heat exchangers

The design for a heat pipe heat exchanger mainly comprises of heat transfer calculation and structural design. In thermodynamic calculation, mainly the overall heat transfer coefficient is calculated, the overall heat transfer area is determined on the basis of average temperature difference and heat load, to determine the number of heat pipes needed, and then the fluid pressure drop and heat pipe transfer power are verified. Although in diversified types of structures, the structural design for heat pipe heat exchangers mostly fall in the scope of conventional design, following the relevant provisions in "Safety supervision regulations on pressure vessels" issued by the State Ministry of Labor and in national standards GB150-1999 "Steel pressure vessels" and GB151-1999 "Steel tube-shell type exchangers".

For the design, manufacture and inspection of heat pipes, the National Technological Supervision Administration of China has formulated jointly with relevant departments some standards of People's Republic

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of China, such as "Technical specifications for carbon steel-water heat pipes" and "Technical specifications for carbon steel-water heat pipe heat exchangers for gas-gas heat exchangers", and they will soon be put into implementation. At present, some standards made by certain enterprises are being implemented, such as the enterprise standard of Jiangsu Province- Su Q/B- 25- 86 "Technical specifications for carbon steel-water gravity heat pipes"[10] and heat pipe standard of Liaoning Province-Liao Pan Q34- 88, RH- YQS boiler heat pipe economizer[11], etc.

4 Industrial application of liquid metal heat pipes (high-temperature heat pipes)

With the continual advancement of heat pipe technology, heat pipe type industrial process equipment have been developed and applied, making the heat pipe equipment not only just for recovery of waste heat, but also indispensable highly-efficient heat transfer equipment in some industrial processes. In industrial applications, the heat exchange temperature sometimes is as high as 900~ 1000℃, and obviously, carbon steel-water heat pipes cannot be used under such conditions. Therefore, research on industrial applications of liquid metal heat pipes (high temperature heat pipes) has been conducted. Nanjing University of Chemical Technology successfully developed a high-temperature heat pipe steam generator in 1990[13]. It is used for recovery of high-temperature waste heat in small fertilizer plants, and has been operating up to now. Subsequently, it developed a high-temperature heat pipe gas-gas heat exchanger, which was awarded the State Invention Prize in 1996. For large scale industrial promotion and application, the "research on heat transfer characteristics of liquid metal heat pipe and equipment" is conducted as financed by the State Planning Commission, to solve such issues as heat transfer characteristics, safety and economy of liquid metal heat pipe and equipment.

4.1 Research foundation for industrial application of liquid metal heat pipes

4.1.1 Research on heat transfer characteristics of liquid metal heat pipes and equipment

(1) Research on heat transfer performance and limits of liquid metal heat pipes

According to the requirements of research, highly-effective high-temperature heat pipes were developed, and a testing system for single-pipe performance for high temperature heat pipes was set up as shown in Fig. 7. The experimental results show: the heat transfer ability of a single highly-effective high temperature heat pipe exceeds or equal to 40 kW, the pipe size: ≊57 × 3.5 × 2800 mm, and the calculation formula for heat transfer resistance within a high-temperature heat pipe is obtained;

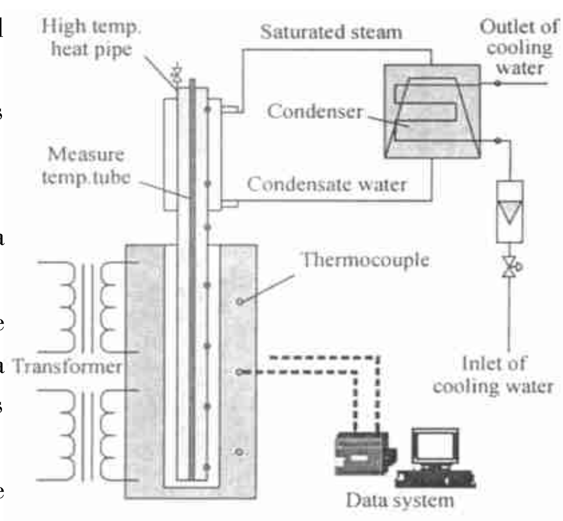

Fig. 7 High temp. heat pipe power-test apparatus

(2) Testing research on overall heat transfer characteristics and the efficiency of high temperature heat pipe heat exchangers.

An experimental system for overall heat transfer characteristics of gas-gas high-temperature heat pipe heat exchangers is set up by simulating the actual industrial conditions (Fig. 8), and the following results are obtained (the recommended applicable range of Re number being 1900~ 20000):

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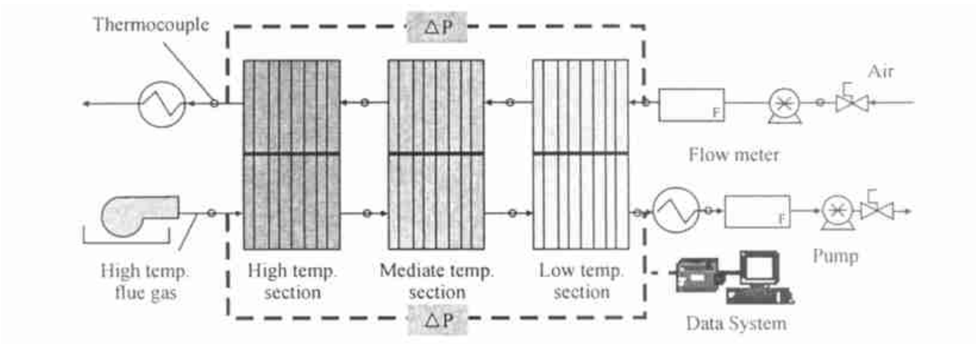

Fig. 8 Schematic of test system for high temperature heat pipe exchange performance

The dimensionless number formulas for calculating the heat transfer coefficient of a high-temperature heat pipe heat exchanger:

$$\alpha_h = 0.1098\left(\frac{\lambda_h}{d}\right) Re_h^{0.6256} Pr_h^{\frac{1}{3}}$$

$$\alpha_c = 0.0938\left(\frac{\lambda_c}{d}\right) Re_c^{0.6367} Pr_c^{\frac{1}{3}}$$

The dimensionless number formulas for calculating the friction coefficient of pressure drop:

$$f = 1.991 Re^{-0.144358}$$

4.1.2 Research on safety in industrial application of liquid metal heat pipes

With the continual expansion of application of high-temperature liquid metal sodium heat pipes, safety has become a primary issue to be solved. For the application of sodium heat pipes in steam generators, theoretical analysis and experimental studies on the sodium-water reaction in sodium heat pipes were conducted[15] with a simulation testing system for sodium-water reaction to simulate the conditions of pipe wall rupture in the condensing section of the high-temperature sodium heat pipe steam generators, as shown in Fig. 9. The pressure pulse peak values of sodium-water reaction were measured to find its regularity of reaction.

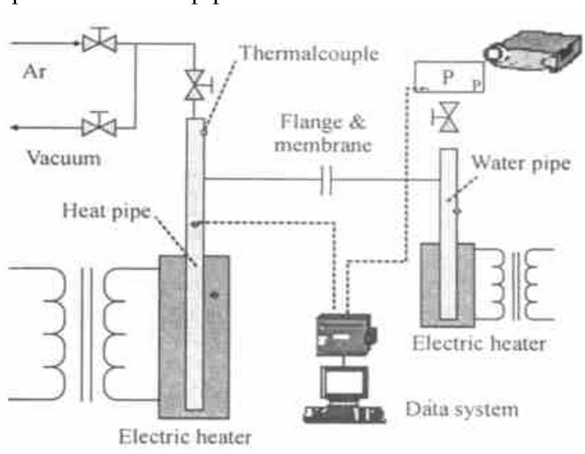

Fig. 9 Test system of sodium-water reaction in heat pipe

It can be seen from the experimental results that there is certain regularity in the sodium-water reaction in a heat pipe. The reaction proceeds in two phases. The first phase is intense explosion reaction, but the pressure does not reach the peak value during this phase; while the second phase is a slow reaction, equivalent to a small scale leakage (50 mg/s~ 10 g/s) in the sodium-water reaction in a fast-neutron reactor, and the reaction rate is less than 1 g/s. So the following conclusions are reached:

(1) The sodium-water reaction in a heat pipe is a quantitative sodium-water reaction in a limited space, and when the heat pipe is damaged to become an open system, the pressure rise in the pipe is suppressed;

(2) The rise of temperature and pressure resulting from the sodium-water reaction in the heat pipe is related to the quantity of sodium filled, and its pressure and temperature rise is accomplished within 10 s to several minutes;

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(3) The result of single heat pipe leakage in the sodium heat pipe steam generator is only the failure of a single heat pipe, not affecting the operation of the adjacent pipes and the system.

4.1.3 Research on compatibility of low-alloy steel-liquid metal heat pipes[16]

For the promotion and application of high-temperature heat pipe heat exchangers in industries, equipment cost is one of the key factors. In this research, two low-alloy steel materials, 15CrMo and 12CrMoV, were used for a 2000 h life comparison test with stainless steel, and the purpose is to find a heat pipe which is simple in manufacture process, stable in performance and low in cost for the operation temperature range of 450~600 ℃, so as to provide a basis for the industrial application of low-alloy steel high-temperature thermosyphons.

Table 4 Experimental parameters

No	Size	Material	Working fluid	Fluid weight	Filling ratio	Time/h	Vapor temp/℃
1	≊38×6	12CrMoV	Na	55	28%	2100	500
2	≊38×6	12CrMoV	K	50	28.8%	2100	480
3	≊32×3	1Cr18Ni9Ti	Na	85	43.7%	2020	450
4	≊32×3	15CrMo	Na	90	46.3%	1940	480
5	≊32×3	15CrMo	K	30	17.5%	450	450

The main test parameters are given in Table 4. All five heat pipes are 720 mm long, the evaporating section being 400 mm and condensing section 270 mm. They were heated using electric heating furnace, with the upper ends cooled naturally by air. The research results are:

(1) Corrosion of alkali metals (sodium and potassium) to the internal wall surface of low-alloy steel heat pipes is mainly caused by the activation of oxygen carried by impurities and the refluxing and washing of liquid media, and the corrosion in the condensing section of the heat pipe is more serious than that in the evaporating section. After operation for 2000 h, the corrosion pits in the condensing section is generally below 60 μm. The corrosion rates are: 0.131~0.219 mm/a with 12CrMoV, 0.174~0.262 mm/a with 15CrMo and 0.394~0.438 mm/a with 1Cr18Ni9Ti.

(2) Under high oxygen content condition, the corrosion type of alkali metals on the metal materials is basically identical. The corrosion by alkali metals on 15CrMo is mainly homogeneous physical dissolution, and an even loose corrosion layer is formed on the inner wall of the heat pipe. Their corrosion on 12CrMoV is mainly local cracking corrosion, which develops irregularly. And the corrosion behavior of 1Cr18Ni9Ti is selective dissolution at crystal boundary, resulting in gradual separation of crystalline grains.

As oxygen in impurities is the key factor affecting the compatibility of heat pipes, by improving the present heat pipe manufacture process and alkali metal purification process and increasing the vacuum of heat pipes can effectively reduce the corrosion of alkali metals on the shell materials of heat pipes, and prolong the service life of heat pipes.

4.1.4 Simulated optimization research on high-temperature heat pipe heat exchangers[17]

A high-temperature heat pipe heat exchanger is a combined heat pipe heat exchanger comprising heat pipes filled with different working fluids. It can be divided into three sections according to different working fluids in the pipes: high-temperature section, mediate temperature section and low temperature section. The high-temperature section normally consists of sodium and potassium heat pipes, the intermediate temperature section normally of naphtha heat pipes and the low-temperature section of carbon steel-water heat pipe. As the internal working temperature ranges suitable for these three types of pipes are not well linked, while the temperature field of cold and hot fluids outside the pipes is continuous, the design for the linking

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parts for different temperatures in a high-temperature heat pipe heat exchanger is complicated. In addition, there is a great difference in the inlet and outlet temperature of the cold and hot media in a high-temperature heat pipe heat exchanger, and therefore it cannot be simply solved with conventional physical means. In literature[17], a simulated optimization calculation method is proposed and it has successfully solved the problem of simulation calculation for high temperature heat pipe heat exchangers, providing a powerful theoretical basis for structural optimization of high-temperature heat pipe heat exchangers. From the viewpoint of practical engineering applications, it has greatly reduced the cost of high-temperature heat pipe heat exchangers, and laid a fairly solid theoretical foundation for the further development and application of high-temperature heat pipe heat exchangers.

4.2 Example of industrial application of liquid metal heat pipe technology

4.2.1 High-temperature heat pipe hot air furnace[18]

With the development of fine chemical industry, higher requirements have been raised on the spray drying technology for powder materials, which require a hot air of 450~ 600℃ or even higher temperature in many applications. It is quite difficult to heat the air to such a temperature range with conventional heat exchange equipment. If the flue gas of fuel is used directly, pollutants may be carried with it, rendering the product quality not up to the specification. Fig. 10 shows a new heat pipe high-temperature hot air furnace (put into operation in Feb., 1997). Its heat transfer capacity is 1163 kW and its parameters are as shown in Table 5. This unit uses coal as raw material to get hot air free of any contamination. The water content of the dried product can fall below 2%, and product quality reaches or even exceeds the international standards. The increase in hot air outlet temperature depends on the materials used in the high-temperature zone. With a small amount of NiCr high-temperature alloy steel as the heat pipe material, high-temperature hot air with a temperature above 800℃ can be obtained.

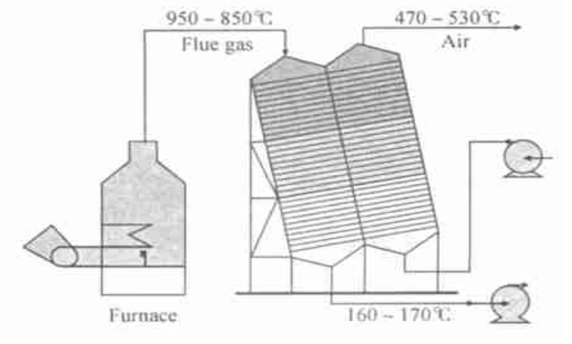

Fig. 10 High temperature heat pipe hot air furnace

4.2.2 High-temperature heat pipe heat extractors[19]

A high-temperature heat pipe heat extractor for flue gas from catalytic regenerator is as shown in Fig. 11. The heat in the catalytic regenerator flue gas is extracted using high-temperature heat pipes to ensure that the temperature of the flue gas entering the next stage of turbine is below or equal to 645℃. This equipment is now operating in a petrochemical plant and it has met all the expected objectives. It is still operating well after practical operation for one and a half year, completely solving all previous problems. Its main technical parameters are shown in Table 6. This research result has fully proved the successful application of the high-temperature heat pipe technology in high-temperature heat extraction, and it has extensive application fields and very high economic values for promotion.

Table 5 Parameters of high temperature heat pipe hot air furnace

	Flue gas	Air
Flow rate/ (Nm^3/hr)	4 300~ 4 900	6 000~ 6 500
Inlet temp. / ℃	850~ 950	20
Outlet temp. / ℃	150~ 170	470~ 530
Heat recovery	1163 kW	

Table 6 Parameters of high temperature heat pipe heat extractor

	Cold side Saturate water	Hot side Flue gas
Flow rate/ (Nm^3/h)	20000 kg/h	10 000 Nm^3/hr
Inlet temp/ ℃	253	700
Outlet temp/ ℃	253	645
Pressure drop / Pa	3 800	220
Heat recovery / kW	2 438	

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5 Research and development of heat pipe chemical reactors under high temperature and high pressure

With its superior characteristics, heat pipe technology is playing a more and more important role in the waste heat recovery, energy-saving and environmental protection units and in industrial process equipment. To reform the chemical reactor, key equipment in industrial processes with the heat pipe technology will not only be beneficial to energy optimization of the reactor itself. More importantly, it is good to chemical reaction to raise the output and yield, thus bringing the industrial production equipment level onto a new step. Our university has been engaged in the research and development of heat pipe chemical reactors since the beginning of the 1990s with the financing from the Science and Technology Commission of Jiangsu Province, and has got achievements in laboratory study, pending further industrialized study. The following is a brief presentation on a heat pipe chemical reactor "infinitely approaching" the optimal reaction temperature under high-temperature and high-pressure conditions (480 ℃, 32 MPa).

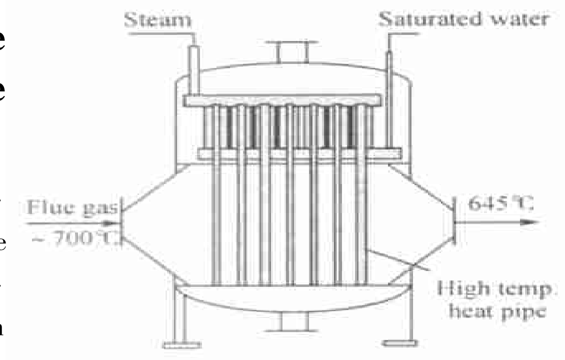

Fig. 11 Schematic of high-temperature heat pipe heat extractor

5.1 Concept of a heat pipe chemical reactor "infinitely approaching" the optimal reaction temperature

Research was conducted on the ammonia converter, the key equipment in fertilizer production. The heat pipe technology is adopted to develop a heat pipe chemical reactor infinitely approaching the optimal reaction temperature on the basis of the research results on the heat transfer characteristics of vapor-liquid two-phase flow in the helical tube of the loop heat pipe evaporator[22], to optimize the temperature distribution on the reactor bed and increase the net ammonia yield without increasing the flow resistance. The main concept is: the evaporator of the loop heat pipe is placed in the converter using the adiabatic reaction and indirect heat exchange structure, to divert the heat out of the converter to produce steam, so that the reaction temperature approaches the most suitable value for reaction, thereby increasing the net ammonia yield. Specifically, the structure is divided into finite section model and infinite approaching model, with the operation curves as shown in Fig. 12. With the so-called finite section model, there are finite and fixed number of catalyst layers in the converter, and this model is suitable to ammonia converters with adiabatic reaction and indirect heat exchange between sections, as well as axial-radial ammonia converters; the infinite approaching model is suitable to axial ammonia converters, in which the loop heat pipes are placed in the catalyst layers, and the reaction heat is extracted while the reaction is going on, so that the temperature of the catalyst layers can infinitely approach the optimal reaction temperature curve.

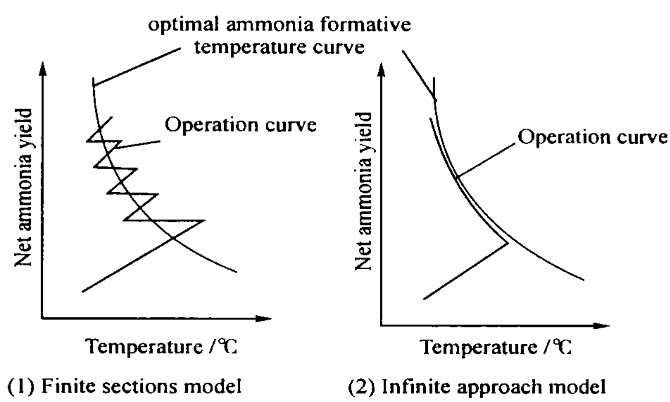

Fig. 12 Operation curves

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5.2 Control and process simulation calculation for optimal reaction temperature for heat pipe ammonia converters

The software for simulation calculation was developed, with its main interface pages as shown in Fig. 13. The master program of the simulation calculation is to solve in parallel the kinetic equations and thermal equilibrium differential equations using an accurate differentiation method under given conditions (pressure, gas amount and gas composition, etc.), to get the temperature and ammonia content distribution in the catalyst layers, then the results are compared with the most suitable temperature curve and the set conditions, to adjust the calculation parameters and obtain the optimized results. The results show that the net ammonia yield is over 19% in all cases, 6 percentages higher than the present values in ammonia converters (about 13%). This proves that heat pipe type ammonia converter with infinite approaching optimal reaction temperature model is worthy further development and promotion, with broad prospects.

Fig.13 Main interface pages of simulation calculation

6 Concluding Remarks

There are two main subjects in the research, development and application of heat pipe technology in industries: one is technology extension and application. This needs to standardize and systematize the present fairly mature heat pipe products, and to normalize their design, manufacture and quality inspection, so that they become conventional equipment in industrial production, thereby further widening the application of heat pipe technology. The second is research and development. This needs to bring into full play the characteristics of the heat pipe technology, and to further develop new type high-efficiency heat & mass transfer equipment by integrating with other areas of sciences, to bring changes to some traditional equipment and to improve the safety, reliability and efficiency of systems.

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热管技术研究、发展与工业应用

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[摘要] 介绍了一些热管技术在工程的典型应用, 包括废热回收设备和工业过程设备. 水碳钢热管技术在许多工程领域都得到了成功应用, 如: 用于废热回收、节能与环境保护的空气预热器和废热锅炉. 液态金属高温热管技术在过程装备得到了广泛应用, 高温热空气发生器和热管技术在化学反应器中也能发挥作用, 如在氨合成塔中的应用. 热管技术的成功应用是建立在热管技术的基础研究之上的, 这些研究包括: 热管内汽液两相流动与传热、热管传热极限、热管传热强化和热管材料相容性与热管的寿命等方面理论和实验研究. 高效传热与传质的热管设备在许多工程应用领域将会得到越来越重要的应用.

[关键词] 热管技术, 典型应用, 发展

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