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Rapid communication

Experimental study of a remote sealing method for vacuum leak

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A B S T R A C T

Vacuum leak is a critical issue for all devices having vacuum system, especially for the large complex experimental facilities. They often have vacuum components integrated which are inaccessible once the assembly was finished. Therefore, if any unacceptable vacuum leaks occur on the cooling/baking channels of the vacuum components, the machine, at least partially, needs to be disassembled before the maintenance, which would cause extensive experimental program downtime and financial costs. An innovative remote sealing method has been studied to permanently repair such vacuum leaks by injecting a sealant called KH-1714 into the channels with pressurized inert gas. Three experiments, that at 10–20 m away sealing different types of leaked components (bellows, circular pipe or rectangle pipe) with leak rates at the level of 10^{-6}–10^{-5} Pa m^3/s, were done to study the feasibility and reliability of the method. The details of the experiments and results were presented and discussed.

Large scientific facilities such as accelerator [1] and tokamak [2,3] have big vacuum chambers in which various vacuum components are installed. The vacuum components always have pipes/channels for the purpose of cooling or baking, such as the thermal shield (TS) [4] and the plasma facing components (PFCs) [5] in a tokamak. Fig. 1 shows the route of the helium cooling pipe for one sector of the TS of the Experimental Advanced Superconducting Tokamak (EAST). Both of the TS and the PFCs must have very good vacuum tightness. Otherwise, it may lead severe accidents, for example the quenching in the superconducting magnets or the erosion/broken of the PFCs. Therefore, it is necessary to repair the TS/PFCs once an unacceptable vacuum leak occurs. However, generally it will cause extensive experimental program downtime and financial costs. The reason is that (1) the TS/PFCs are inaccessible once the assembly was finished, (2) the vacuum chamber has to be opened before the maintenance and (3) the maintenance is carried out in an extremely complex context. Thus, it is quite important to seal such vacuum leak on-line, neither shutting down the machine nor opening the vacuum chamber, from the viewpoints of safety operation and economy.

To seal the vacuum leak in the TS/PFCs on-line, the general issues are:

- Sealant chosen. The sealant must be compatible with the clean ultra-high vacuum, and be capable of operating at cyclic high/low temperatures and sealing vacuum leak as big as possible.
- How to transport the sealant to the place where vacuum leak occurs? The TS/PFCs are integrated inside the vacuum chamber and the specific location of the vacuum leak is unknown. The sealant needs to be transported along the sophisticated channel, from the openings of the channel at the port of the vacuum chamber to some tens of meters away.
- How to assure the sealing quality?

In the short communication, a remote sealing method is proposed to permanently seal such vacuum leaks by injecting the sealant into the channel by pressurized inert gas. Current progress of the experimental study is presented.

In the method sealant chosen is an important step. There are not so many choices in commercial market due to that the sealant is not a frequently-used product, such as the pumps, in a vacuum system. It is more often used at the occasion of accident. To the best of our knowledge, in general there are two types of sealant. One is solid [6,7]. The Torrseal® produced by Agilent [6] is widely used [8,9]. The other is liquid. Through the internet, the Vacseal® [10] and the Celvaseal® [11] vacuum sealants are commonly available. They have very good vacuum properties according to the instructions. Here, the sealant called KH-1714, produced by Nanchang Kete Precision Science and Technology Ltd. in China, is used. It also has very good vacuum properties. By hand spraying, it is successfully used in EAST

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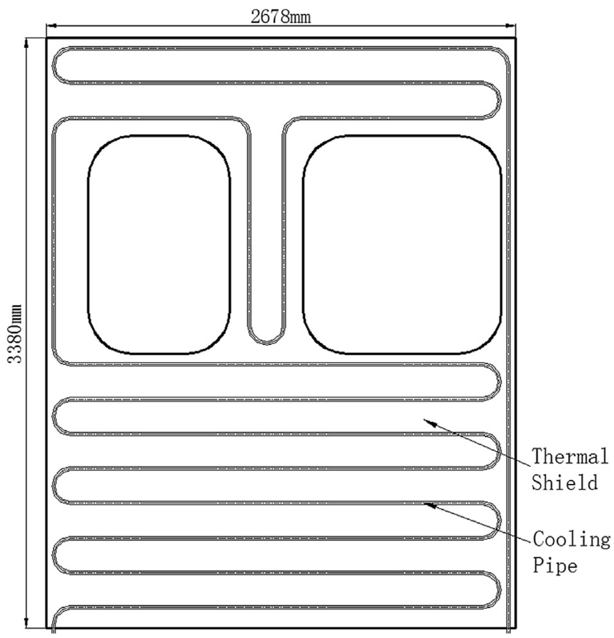

Fig. 1. Route of the cooling pipe for one sector of EAST thermal shield.

vacuum group for sealing the vacuum leaks lower than 10^{-7} Pa m^3/s, which occur on the vacuum components and are accessible for manual operation. The sealant KH-1714.

- is a colorless transparent liquid with low viscosity.
- can easily penetrate into micropores in the materials such as metal, ceramic and glass.
- can seal the leak at or lower than the level of 10^{-6} Pa m^3/s.
- can be used at temperatures ranging from −190 °C to 350 °C and be operated at cyclic high/low temperatures.
- has a low out gassing of lower than 10^{-11} Pa m^3/s per square meters, ideally for sealing leaks in high or ultra-high vacuum system.

All the liquid sealants are designed and produced for hand spraying. Definitely, the big challenges existing in the remote sealing are that how to transport the sealant to the position of vacuum leak and assure the sealing quality. The principle of the proposed remote sealing method is that: (1) firstly, at the port of the vacuum chamber make one inlet opening and one outlet opening for the channel of the leaked component; (2) secondly, with the phenomenon of siphon and pushing force of the pressurized inert gas, the sealant KH-1714 is transported from the inlet opening to the position of vacuum leak, then continue to run along the channel and finally drains at the outlet opening; (3) thirdly, by the control of valves in the remote sealing system, the pressure in the channel is periodically changed so that the sealant KH-1714 can be atomized and would deposit on to the position of vacuum leak; (4) finally, after a time of solidification, the vacuum leak is sealed properly.

Experiments were done to study the feasibility and reliability of the method. As schematically shown in Fig. 2, the experimental system is composed of the pressurized pure helium gas, the sealant KH-1714, three valves, two connecting pipes, the vacuum pipe, and the vacuum chamber. The connecting pipe I, with the same inner diameterd_1, connects the helium gas, to the vacuum pipe. The connecting pipe II with inner diameter d_2 connects the sealant KH-1714 to the vacuum pipe. The vacuum pipe, with the length L, models the sophisticated channel of the vacuum component. It may has the features of climbing up/down (height, h_{up}/h_{down}) and a number of circles (parameters, $n \times d_3$). The part of the vacuum pipe, where the vacuum leak occurs, locates inside the vacuum chamber. It may be the bellows, the normal circular pipe or the rectangle pipe.

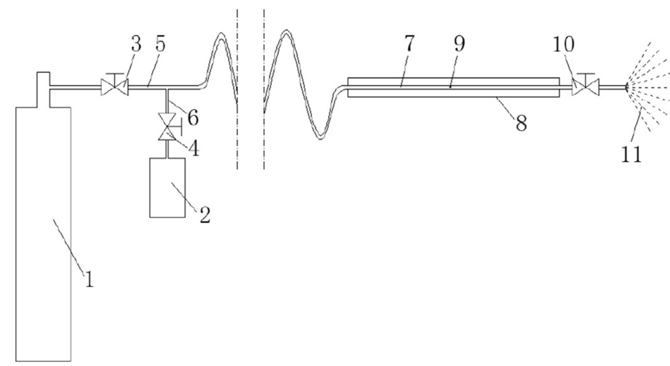

Fig. 2. Schematic sketch of the experiment set-up. 1-pressurized pure helium gas, 2-sealant KH-1714, 3-valve I, 4-valve II, 5-connecting pipe I, 6-connecting pipe II, 7-vacuum pipe, 8-vacuum chamber, 9-vacuum leak location, 10-valve III, 11-atomized sealant KH-1714.

The general operation sequence of the remote sealing experiment is the following.

(a) Set up the experimental system and make sure all the valves are shut off at the beginning.
(b) Open the valve I to supply the pure helium gas and control the gas pressure P; and then open the valve II to supply the sealant KH-1714.
(c) After a time of t_1 seconds, open the valve III.
(d) After another time of t_2 seconds, shut off the valve III. Then after t_1 seconds, open the valve III again.
(e) Repeat the step (d). With this control way, the sealant KH-1714 would be atomized and intermittently run along the vacuum pipe. When the atomized sealant KH-1714 is observed at remote opening of the vacuum pipe, as schematically shown in Fig. 2, then repeat m times more of the step (d).
(f) At last, in sequence shut off the valve II and the valve I.
(g) The steps (a)–(f) is an entire operation of a remote sealing procedure. If needed, the procedure could be repeated n times for sealing big vacuum leak at the level of 10^{-6}–10^{-5} Pam^3/s or enhancing the sealing quality. The break time between two remote sealing operations is t_3 hours.

Among the many parameters described in the above two paragraphs, d_1, L, h_{up}, h_{down} and $n \times d_3$ are the dimensions of the vacuum pipe, which should be consist with the real features of the channel in the vacuum components. While the others, d_2, P, t_1, t_2, m, n and t_3 are setting parameters for remote sealing process. Three experiments were conducted with different parameters as listed in Table 1. In experiment 1 the vacuum pipe has a leak rate of 2.17×10^{-5} Pa m^3/s (measured by helium spraying test, the same for the following two vacuum leaks) in the segment of bellows. In experiment 2 the vacuum pipe has a leak rate of 2.7×10^{-6} Pa m^3/s in the normal segment of circular pipe. In experiment 3 the vacuum pipe has a leak rate of 1.28×10^{-5} Pa m^3/s in the segment of rectangle pipe. During the experiments, the pressure in the vacuum chamber is about 1 Pa.

The leaked parts were leak tested at different helium pressure after the experiments. The results are plotted in Fig. 3.

The bellows in the experiment 1. The bellows was leak tested 3 h after the experiment. Firstly with helium spraying test, the leak rate

Table 1
Technical parameters for the three experiments.

Parameters	Number of experiment		
	1	2	3
Where vacuum leak occurs	Bellow $\phi 14\times 1$ mm	Circular pipe $\phi 14\times 1$ mm	Rectangle pipe $18\times 18\times 15$ mm
Leak rate (Pa m^3/s)	2.17×10^{-5}	2.7×10^{-6}	1.28×10^{-5}
Pressure in the vacuum chamber, Pa	~1	~1	~1
d_1, mm	12	12	12
d_2, mm	1	1	1
L, m	10	20	20
h_{up}, m	3	2.5	3
h_{down}, m	3	2.5	3
$n\times d_3$	–	$6\times \phi 0.4$ m	$6\times \phi 0.5$ m
P, bar	4	1.2	1.2
t_1, s	2	12	5
t_2, s	2	5	5
m	10	6	8
n	2	1	2
t_3, h	3	–	3

is 1×10^{-11} Pa m^3/s. Then with pressurized method, the leak rate goes up to 1.7×10^{-10} Pa m^3/s at 1 bar helium pressure. With helium pressure increased, the tendency of the leak rate is increasing although fluctuations were observed. The fluctuation is may due to that the helium pressure in the bellows was still not stable when the leak rates were recorded at the helium pressure of 2 bar and 4 bar. At helium pressure of 5 bar, the leak rate is 5×10^{-10} Pa m^3/s, much lower than the original one, which means the vacuum leak is sealed by the sealant KH-1714. Normally the level of 10^{-10} Pa m^3/s is the acceptable leak rate for a vacuum component in a tokamak.

The circular pipe in the experiment 2. The circular pipe was leak tested 24 h after the experiment. All the leak rates were recorded when the circular pipe was filled by the setting pressurized helium gas and the pressure was maintained at least 5 min. This is also true for the rectangle pipe. Firstly with helium spraying test, the vacuum leak is 2.4×10^{-10} Pa m^3/s. Then with pressurized method, the leak rate is increased slowly when the helium pressure is increased. At helium pressure of 6.5 bar, it is 4.7×10^{-10} Pa m^3/s, which also indicates that the vacuum leak is sealed properly.

The rectangle pipe in the experiment 3. The rectangle pipe was leak tested 3 h after the experiment. Firstly with helium spraying test, the leak rate is 3.2×10^{-10} Pa m^3/s. But, for leak test with pressurized method, once the pressurized helium gas is injected the leak rate is quickly increased up to the level of 10^{-4} Pa m^3/s, which means the remote sealing attempt is failed. At the first analysis of the reasons of failure, three factors were considered. (1) The time of 3 h for solidification of the sealant KH-1714 is not long enough. (2) The vacuum leak occurs on one weld of the rectangle pipe and the weld has excess weld metal. So, if the sealant KH-1714 comes from one side of the excess weld metal while the vacuum leak is at the other side, then it is difficult to form a thick enough layer of film of the sealant KH-1714, resulting in the failure. (3) The section of the rectangle pipe is rectangle, while for the other two leaked components it is circular, which definitely lead to quite different fluid field of the sealant KH-1714 inside the pipe. This should influence the formation of the layer of the film.

One additional experiment was carried out to investigate the reasons of failure. In this experiment, the set-up is the same to the experiment 3 as shown in Fig. 1 and the Table 1. One point must be mentioned that the rectangle pipe was turned around between the two remote sealing operations to eliminate the influence of the excess weld metal. The leak test was done 24 h after the experiment. The leak rate is still at the level of 10^{-5} Pa m^3/s. As a result, it is probably that the first two factors as described in the above paragraph are not the reasons for the failure.

In conclusion, it can be stated that in principle the proposed remote sealing method, by injecting the pressurized and atomized sealant KH-1714 into the channel of the leaked component, has the ability of on-line sealing vacuum leaks for the vacuum components embedded deeply in the vacuum chamber.

The remote sealing experiments were carried out for three different leaked components, the bellows with a leak rate of 2.17×10^{-5} Pa m^3/s, the circular pipe with a leak rate of 2.7×10^{-6} Pa m^3/s and the rectangle pipe with a leak rate of 1.28×10^{-5} Pa m^3/s. The results indicate that the vacuum leaks in the bellows and the circular pipe were successfully sealed, remotely at 10–20 m away. The leak rates were decreased to the level of 10^{-10} Pa m^3/s, even at 5 bar helium pressure.

While for the rectangle pipe, the vacuum leak was not sealed properly. The reason might be that the rectangle section is not good for the sealant KH-1714 to be deposited onto the inner surface of the pipe and it is difficult to form the needed thick layer of the film. It is necessarily to be investigated further.

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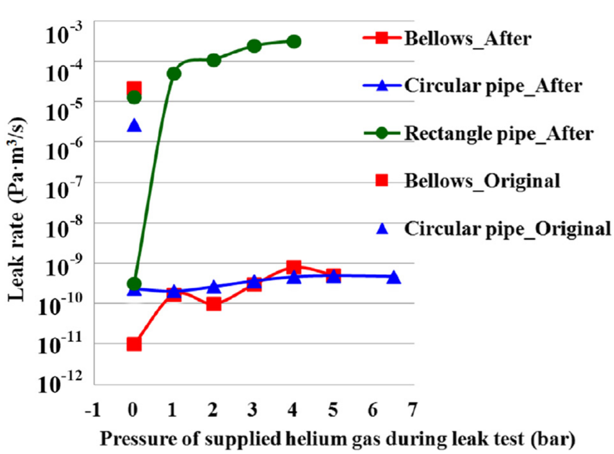

Fig. 3. Leak rates of the three tested leaked components, i.e., the bellows in the experiment 1, the circular pipe in the experiment 2 and the rectangle pipe in the experiment 3. In the figure, 'Bellows_Original' and 'Bellows_After' represents the leak rate of the bellows before and after the remote sealing operation, respectively. The other four instructions could be explained in the same way.

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