Korean J. Chem. Eng., **26**(4), 1004-1008 (2009)
DOI: 10.1007/s11814-009-0167-x

Analysis of micro-leak sodium-water reaction phenomena in a sodium-cooled fast reactor steam generator

Ji-Young Jeong*,†, Tae-Joon Kim*, Jong-Man Kim*, Byoung-Ho Kim*, and Nam-Cook Park**

*Fast Reactor Technology Development Division, Korea Atomic Energy Research Institute, Korea
**Chemical Engineering Division, Chonnam National University, Korea
(*Received 15 March 2007 • accepted 31 December 2008*)

Abstract−The effects of the sodium-water reaction by small water/steam leaks on 2.25Cr-1Mo and Mod.9Cr-1Mo steels have been studied. Test specimens were exposed to small leaks of water/steam in 300 °C stagnant sodium. The phenomenon where the size of the nozzle hole became larger with time was observed for the two types of material. Enlargement rate was slightly faster in the 2.25Cr-1Mo steel than in the Mod.9Cr-1Mo steel. Test results of the enlargement rate of the nozzle hole itself with an increasing duration of the steam injection were analyzed by using SEM and CAMSCOPE images. The maximum reaction temperature appeared at a 17 mm point from the measuring tool, which agrees with the maximum distance that was affected by a jet flame.

Key words: Sodium-water Reaction, Small Leak, Sodium-cooled Fast Reactor, Steam Generator, Wastage, Self-wastage

INTRODUCTION

Sodium-cooled fast reactors adopt sodium-heated steam generators in a secondary sodium circuit to raise the steam to drive the turbine. In most cases these steam generators are of a shell-in tube type, with a high pressure water/steam inside the tubes and low pressure sodium on the shell-side, with a single wall tube as a barrier between these fluids. Therefore, if there is a hole or a crack in the heat transfer tube, a leakage of water/steam into the sodium may occur, resulting in a sodium-water reaction [1-4]. When such a leak occurs, there results an important phenomenon, so-called “wastage,” which may cause damage to or a failure of the adjacent tubes. In general, a wastage is defined as the decreasing thickness of a material caused by the erosion or corrosion effects of the sodium-water reaction products [5,6]. Another type of phenomenon is a “self-wast- age” which is not a wastage on a wall of the adjacent tubes, but which occurs on the inside of the leakage site itself. If a steam generator is operated for some time with this condition, it is possible that it will damage the leak hole itself, which may eventually become a much larger opening. There is a danger that the resultant leak rate caused by a self-wastage might create the state of a small leak, or even an intermediate leak, which would then give rise to the problems of a multi-target wastage. This study and others have observed that the diameter of the nozzle hole grows to become a larger size in a very short time [7,8]. Therefore, it is very significant to predict these phenomena quantitatively from the view of designing a steam generator and its leak detection systems [9,10]. The objective of this study is a basic investigating of the sodium-water reaction phenomena by small water/steam leaks.

THEORETICAL CONSIDERATIONS

1. Chemical Reaction

The representative reaction between the sodium and water/steam can be expressed by the following Eq. (1) form, where A, B, C and D are the reaction constants and Q is the exothermic reaction energy produced by the reaction. Also, the term a is a molar conversion ratio of the unit mole of the water/steam to hydrogen gas.

$$A\cdot Na+H_2O\rightarrow B\cdot Na_2O+C\cdot NaOH+D\cdot NaH+\alpha H_2+Q \tag{1}$$

As shown in the relation, the sodium reacts with the unit mole of the water/steam and then various reaction products, such as NaOH, NaH, Na_2O and hydrogen gas, are produced with an exothermic reaction heat. The NaOH and Na_2O are corrosive, the hydrogen gas causes the pressure on the sodium-side of a steam generator to increase, and the heat causes the temperature of the heat transfer tubes in a steam generator to increase [11]. It is well known that the importance of each of these effects is dependent on the size of a leak. The generated heat and the corrosive reaction products can damage the surrounding tubes, causing the event to escalate.

2. Definition of the Leak Size

2-1. Micro Leaks

Micro leaks are essentially leaks which are too small to be detected. Typically, leaks of less than 0.1 g/s (<0.05 g/s in Japan) can be considered to fall into this category. After an incubation period, such a leak may develop into a small leak.

2-2. Small Leaks

A small leak is one in which a coherent reaction jet of a size capable of impinging on one or two heat transfer tubes is formed, causing damage to them mainly by a wastage. Small leaks are generally in the range of 0.1 to 50 g/s (0.05 to 10 g/s in Japan) [10].

EXPERIMENTAL

1. Experimental Apparatus

Fig. 1 shows the small leak sodium-water reaction test facility used for this study. It mainly consists of two reaction vessels, a sodium circulation circuit, sodium and a steam supply system, a sodium

†To whom correspondence should be addressed.
E-mail: jyjeong@kaeri.re.kr

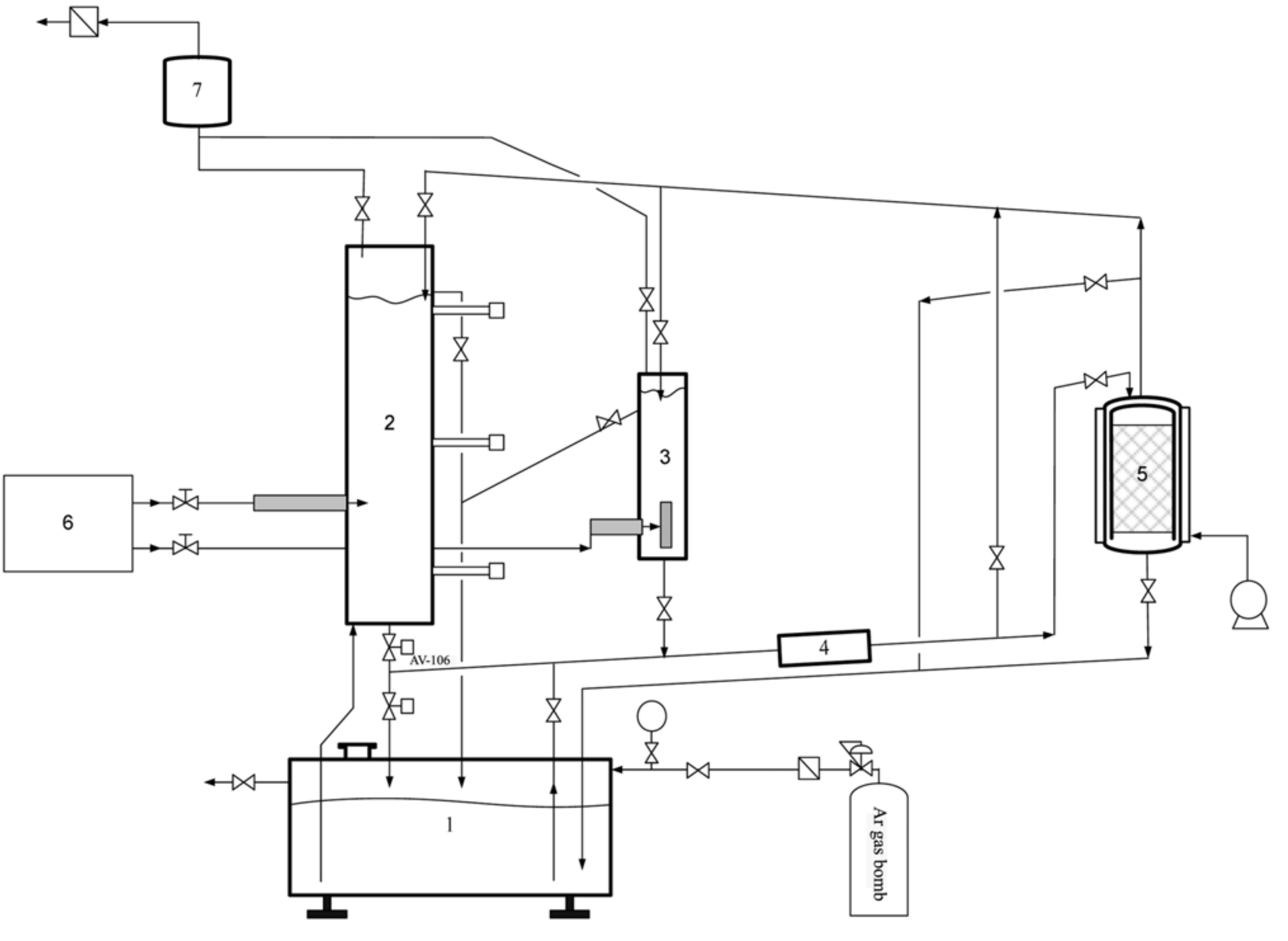


Fig. 1. Schematic diagram of the experimental apparatus.

1. Storage tank
2. Reaction vessel (1)
3. Reaction vessel (2)
4. Electro magnetic pump
5. Cold trap
6. Steam supply system
7. Vapor trap

purification system, and a drain system. The entire loop including the reaction vessel and piping lines are filled with sodium, and a high pressure steam is injected into the reaction vessels. Tests were conducted in two test rigs, one in which an investigation of the wastage phenomena of the heat transfer tube, and one in which a measurement or the frequency band of the reaction sound were implemented. In addition, some basic studies were conducted to help determine the mechanism producing tube wastage during a sodium-water reaction. During the tests, any hydrogen within the entrained sodium was vented from the reaction vessel to the atmosphere through a vapor trap.

2. Experimental Procedure and Conditions

Steam was injected into the sodium from a steam reservoir through an injection nozzle at 87 kg_f/cm^2 pressure and 300 °C temperature. The injection nozzle had openings from 0.1 to 0.3 mm in diameter. And the width, length and thickness of all the nozzles which were used in the tests were 10, 10 and 3.5 mm, respectively. These nozzle specimens were exposed to small leaks of water/steam in 300 °C stagnant sodium. Before opening and after closing the steam injection valve, argon gas was bubbled into the sodium through the injection nozzle in order to prevent a nozzle blockage. The injection duration was determined from the opening and closing signals of the injection valve. 2.25Cr-1Mo steel and Mod.9Cr-1Mo steels were chosen for the test specimen materials.

RESULTS AND DISCUSSION

1. Investigation of the Self-enlargement Phenomenon

A series of tests was carried out to investigate the enlargement rate of the nozzle hole itself with time for 2.25Cr-1Mo and Mod.9Cr-

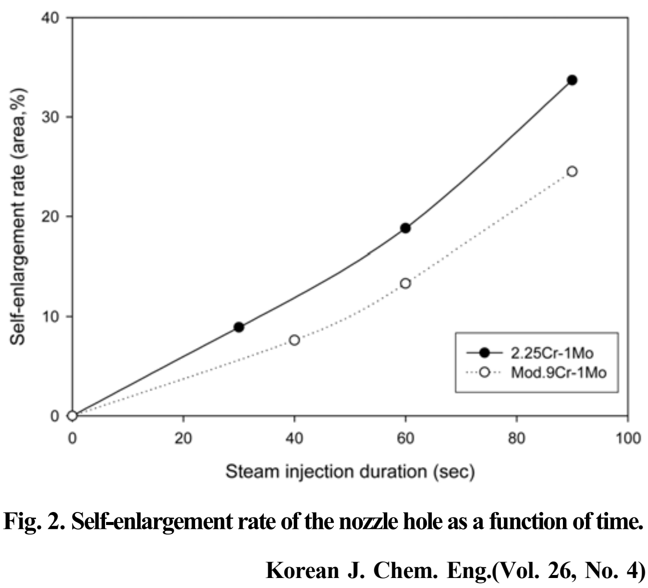


Fig. 2. Self-enlargement rate of the nozzle hole as a function of time.

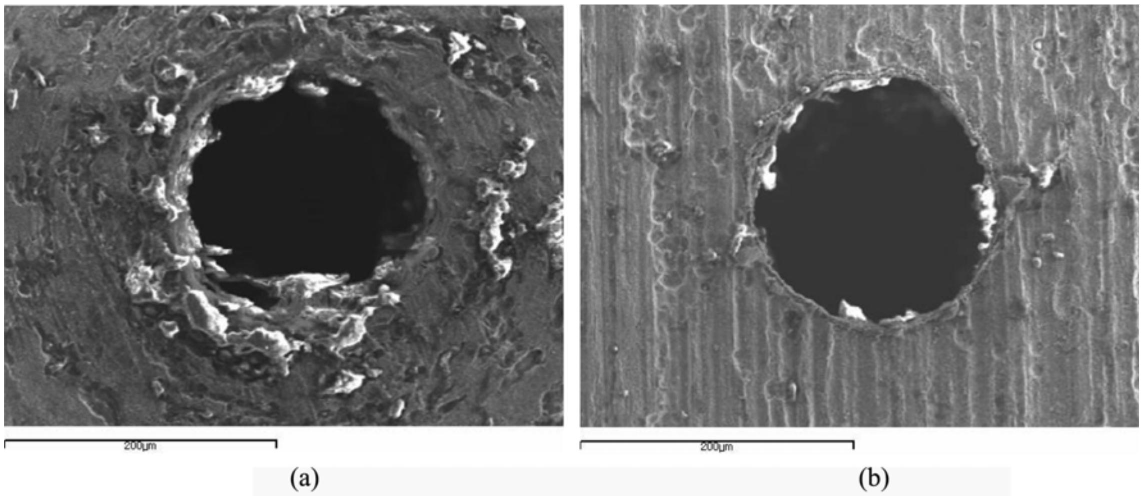


Fig. 3. SEM images of the nozzle surface after the sodium-water reaction.
(a) 2.25Cr-1Mo (b) Mod.9Cr-1Mo

Table 1. Chemical compositions on the nozzle surface

Metal		Elements (wt%)											
		Al	Si	V	Cr	Mn	Fe	Ni	C	Mo	O	Na	Total
2.25Cr-1Mo	Before		0.34		2.27	0.43	95.99			0.97			100
	After the test		0.48		0.79		46.52		4.14		37.68	10.39	100
			0.38		1.68		71.7		7.37	0.85	15.68	2.34	100
9Cr-1Mo	Before	0.2	0.4	0.27	9.39	0.55	87.89	0.18		1.12			100
	After the test		0.34		2.26		33.29		10.1		44.75	8.67	100
			0.25		1.61		61.62		2.0	0.88	24.44	9.65	

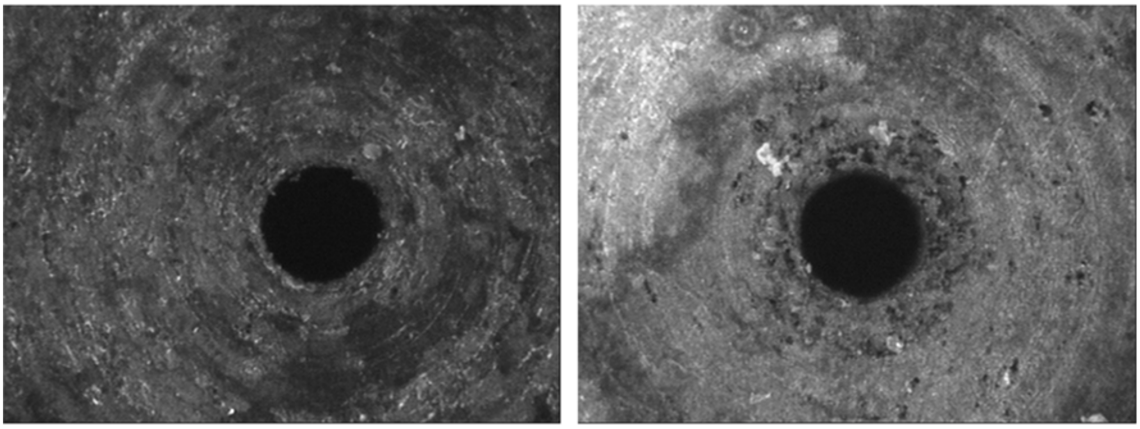
1Mo steels. The initial size of the nozzle hole which was used in the tests was 0.2 mm in diameter, and the initial leak rate was 0.38 g/sec H_2O. The enlargement rate of the nozzle hole itself was measured at 30 second intervals. As shown in Fig. 2, the phenomenon where the size of the nozzle hole became larger with an increasing duration of the steam injection was observed together from the two types of material. Its cause can be accounted for by a hot caustic corrosion of the metal surrounding the nozzle hole and the loose grains of the base metal by the action of the steam jet [8]. This was confirmed by analyzing the nozzle hole and surface on the sodium side using SEM-EDX and CAMSCOPE images. As shown in Fig. 3 and Table 1, complicated oxide compounds are deposited onto the nozzle surface. It is assumed that they are a $(NaOH+Na_2O)\cdot Fe_xO_y$ and $(NaCrO_2+Na_2CrO_4)$ mixture. Enlargement rate was slightly faster in the 2.25Cr-1Mo steel than in the Mod.9Cr-1Mo steel. Based on the cross-sectional area of a nozzle hole after a 90 second injection testing, it is estimated that the size of the nozzle hole became larger by about 1.34 times when compared with the initial value for the 2.25Cr-1Mo steel. The reason for a better resistivity of the Mod.9Cr-1Mo steel against a self-wastage than that of the 2.25Cr-1Mo steel was as follows. Since the nozzle surface is usually covered by the chrome oxide film produced by the sodium-water reaction, an infiltration of the corrosive reaction product (e.g., NaOH) near the nozzle opening may be interrupted by this layer. In general, this phenomenon should occur effectively in Mod.9Cr-1Mo steel due to a high bonding of the chrome with the base metal. Therefore, it can be preliminarily deduced that the resistivity of the Mod.9Cr-1Mo steel against a self-wastage is better than that of the 2.25Cr-1Mo steel. More detailed analysis is to be conducted by using various experimental results regarding the sodium-water reaction in future works. Post test examination showed that the nozzle hole maintained its circular shape (Fig. 4).

2. Analysis of the Reaction Temperature

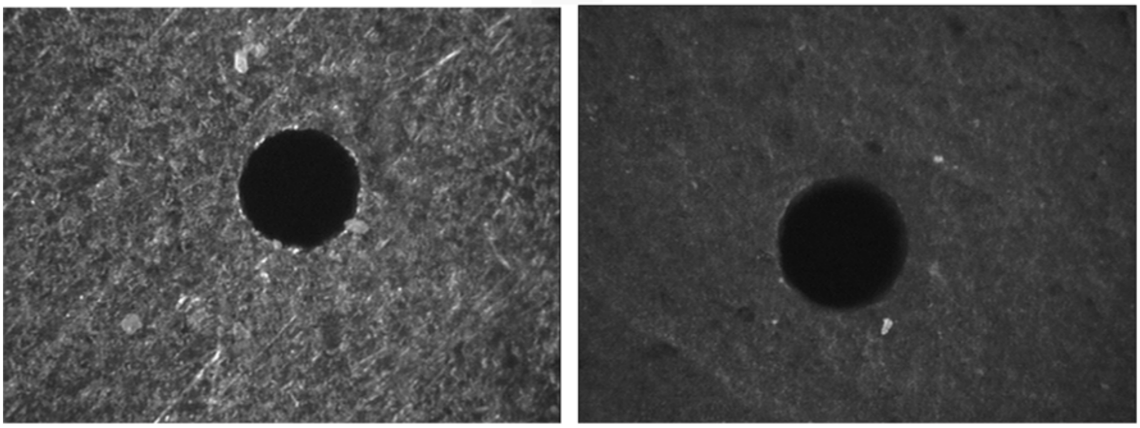
The wastage of the heat transfer tube materials is accelerated by the heating of a tube surface as a result of the heat generated by the sodium-water reaction. Therefore, it is very important to determine the peak temperature within a sodium-water reaction jet from the view of designing a steam generator.

When discussing the effect of small water/steam leaks in sodium-heated steam generators, the expression a "flame type reaction zone" (Fig. 5) is always used [1,12]. The geometrical characteristics of a flame are of practical interest with regards to estimating the consequences of reaction products upon tube bundle materials. The steam jet can be divided into three zones as shown in Fig. 5 [13,14].

- An expansion zone where the steam jet undergoes a rapid depressurization to the sodium side pressure within a short distance from the nozzle opening. In this zone, the amount of H_2O is larger than that of Na.
- A reaction zone with sodium that is characterized by a high temperature superior to that for a vaporization of sodium. The peak temperature will be given at an initial composition of 0.53 mole Na and 0.47 mole H_2O where the two species can react



(a)



(b)

Fig. 4. CAMSCOPE images of the nozzle hole (left; before the reaction, right; after 90sec of the reaction).
(a) 2.25Cr-1Mo (b) Mod.9Cr-1Mo

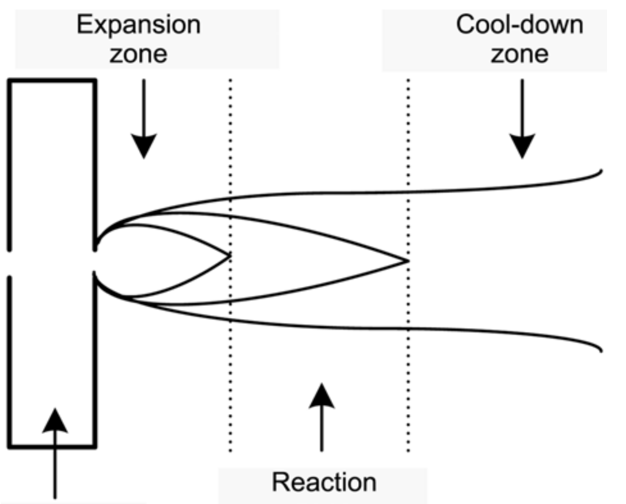


Fig. 5. Model of the flame type reaction zone.

completely.

- A zone where the steam jet cools down due to the supply of fresh and cooler entrained sodium.

Based on the results from the investigations by many authors,

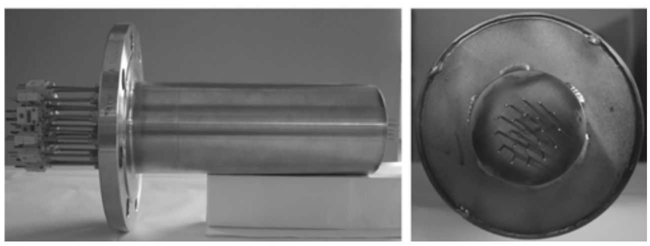


Fig. 6. Reaction temperature measuring tool.

Dumm of INTERATOM derived the following equation [15]:

$$L_{max}=9.3\cdot d_L\cdot \Delta P^{0.5} \tag{2}$$

where L_{max} is the maximum distance affected by a jet, in mm, d_L is the diameter of a nozzle hole, in mm, and ΔP is the steam pressure, in kg_f/cm^2. To predict the influence range of such a reaction zone, a series of tests was conducted. The measuring tool used for the influence range of the reaction flame is shown in Fig. 6. It has twenty-one thermocouples arranged in a concentric circle. Measuring distance for the reaction temperature was determined to be 10, 17, and 27 mm from the measuring tool to consider the neighboring tube space in a steam generator and the maximum jet flame length. As shown in Fig. 7, the maximum reaction temperature appeared at a

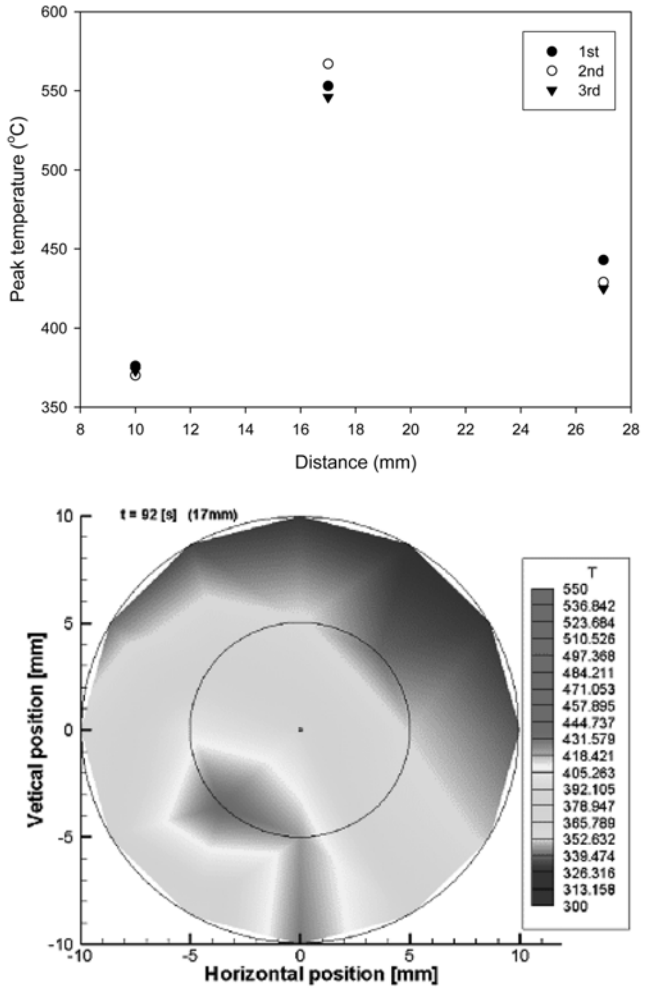


Fig. 7. Maximum reaction temperature as a function of the measuring distance.

17 mm point from the measuring tool. This is the point which agrees with the maximum distance that was affected by a jet flame. But it was very difficult to measure the reaction temperature accurately because of the reactions which occurred instantaneously on a flame surface with a very thin film (0.7-1 mm). In case of the reaction temperature, the cool down zone was higher than that of the expansion zone. We think that this is due to the specific heat difference of these two zones.

CONCLUSIONS

A series of tests was carried out to investigate the enlargement rate of the nozzle hole itself and the sodium-water reaction temperature associated with needle-like jets of a high-pressure water/steam into the sodium side of a steam generator. The size of the nozzle hole became larger with an increased duration of the steam injection both for the 2.25Cr-1Mo and Mod.9Cr-1Mo steels by the well known self-wastage phenomenon. Enlargement rate was slightly faster in the 2.25Cr-1Mo steel than in the Mod.9Cr-1Mo steel. The results of the SEM-EDX analysis showed that complex oxide compounds, formed by a sodium-water reaction, were deposited around the nozzle hole. The maximum reaction temperature appeared at a 17 mm point from the measuring tool, which agrees with the maximum distance that was affected by a jet flame. The data obtained from this study will be used to prepare the design criteria and design analysis procedures for steam generators from the point of view of sodium-water reactions.

ACKNOWLEDGMENT

This study was performed under Nuclear Technology Development Program sponsored by the Ministry of Education, Science and Technology (MEST) of Korea.

REFERENCES

1. M. Hori, *Atomic Energy Review*, **18**, 708 (1980).
2. K. C. Jeong, J. Y. Jeong, B. H. Kim, T. J. Kim, J. H. Choi, D. H. Hahn and E. S. Kim, *J. Ind. Eng. Chem*., **10**, 524 (2004).
3. K. C. Jeong, J. Y. Jeong, B. H. Kim, T. J. Kim and J. H. Choi, *J. Ind. Eng. Chem*., **8**, 283 (2002).
4. R. N. Newman and C. A. Smith, *J. Nucl. Mater*., **52**, 173 (1974).
5. N. Kanegae, K. Hashiguchi, I. Ikemoto and M. Hori, *Nucl. Technol*., **40**, 261 (1978).
6. A. R. Pugh, *Nucl. Energ.-J. BR Nucl*., **11**, 263 (1972).
7. J. R. Donati, M. Grand and P. Spiteri, *J. Nucl. Mater*., **54**, 217 (1974).
8. D. W. Sandusky, *Trans. ANS*, **19**, 106 (1974).
9. J. F. B. Payne, *Nucl. Energ.-J. BR Nucl*., **18**, 327 (1979).
10. A. M. Judd, R. Currie, G. A. B. Linekar and J. D. C. Henderson, *Nucl. Energ.-J. BR Nucl*., **31**, 221 (1992).
11. J. H. Eoh, J. Y. Jeong, S. O. Kim and D. H. Hahn, *Nucl. Technol*., **152**, 287 (2005).
12. R. Hans and K. Dumm, *Atomic Energy Review*, **154**, 611 (1977).
13. F. Roger, K. Y. Park, J. L. Larreau, L. Gbahoue and P. Hobbes, CEA-CONF-7851 (1984).
14. Y. Okano and A. Yamaguchi, INIS-FR-483 (2001).
15. K. Dumm, IWGFR-1, C.8 (1975).