JOURNAL OF MATERIALS SCIENCE **39** (2004) 7003–7008

The eutectic generation effect and chemical modification of thermal lance cutting of concrete

H. WANG
Department of Chemical Engineering, 218 Furnas Hall, SUNY at Buffalo, Buffalo, 14260, USA

P. PRANDA
Combustion, Modeling & Process Control Group Manager, American Air Liquide-Chicago Research Center, 5230 S. East Avenue, Countryside, IL 60525, USA

V. HLAVACEK*
Department of Chemical Engineering, 218 Furnas Hall, SUNY at Buffalo, Buffalo, 14260, USA
E-mail: hlavacek@acsu.buffalo.edu

Thermal lance is one of the methods for concrete cutting/piercing. The burning lance not only provides high temperature to melt the concrete target in the form of lava, but also has a eutectic effect changing the lava melting temperature. The eutectic effects by adding lance material such as FeO, Al_2O_3 and TiO_2 to concrete (SiO_2-CaO) system are discussed. The discussion and concrete piercing experiments both show that, due to eutectic generation effects, aluminum and titanium modified lances are not effective on concrete objects although these lances provide high lance temperature. Iron based lance is the most effective thermal lance due to its eutectic generation effect. Experimental results of cutting improvement by using chemically modified iron lance are presented and the eutectic generation effect in this process is discussed. © *2004 Kluwer Academic Publishers*

1. Introduction

The technique of oxygen thermal lancing has been traditionally used to cut metals. This technology has been developed and widely used since the World War II. Using an improved lance technique - iron core lance [1]—the lance power output was increased and the technology could be applied to concrete cutting.

In the thermal lancing process, a piece of the lance rod (usually made of a low carbon steel tube with the iron wire assembly inside) reacts with oxygen flowing through the center of the metallic tube assembly. The oxidation reaction generates a large amount of heat that is capable of melting/oxidizing the target. Gaseous oxygen that is in excess is blowing off the molten target in the form of lava. The wire core lance burns at a temperature of about 3000°C; hot enough to melt cement, sand and aggregate [2]. Steel reinforcement in the concrete is not an obstacle; on the contrary, it provides additional fuel for the burning process.

Compared with the mechanical cutting of concrete, thermal lance cutting has the following advantages:

- Easy to handle
- Low investment cost
- Precise in cutting holes
- No noise, vibrations, or shocks during cutting
- Cuts both metal and concrete
- Operates in tight and awkward spaces
- Avoids damage, in particular mechanical damage, to the parts of the structure that are to be preserved.

The disadvantages of thermal cutting are as follows:

- The large quantity of smoke which will spread contamination unless is can be contained effectively, cooled and filtered [3].
- High temperature lava is generated during the cutting process which restricts the working environment and requires special care to be taken.

One of the major modifications of the wire core thermal lance is the replacement of the iron with other metals such as aluminum, titanium and magnesium [4, 5]. The adiabatic combustion temperatures of these metals are higher than that of iron. The lance made of these metals is supposed to provide a higher temperature than an iron-based lance.

In this paper the eutectic generation effect of metal oxides (provided by the lance) on the concrete cutting/piercing process is discussed. The ternary phase diagrams (Figs 1, 2 and 3) [6–8] show that lava generated by the iron based thermal lance has a lower

---

*Author to whom all correspondence should be addressed.

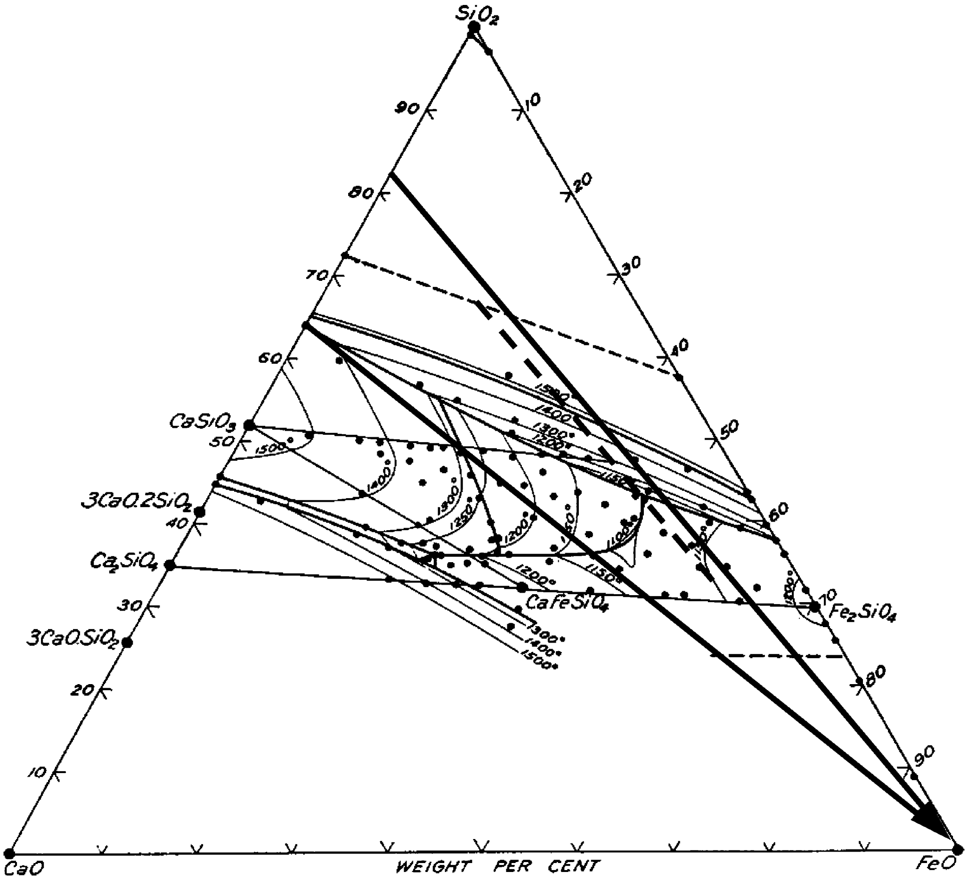

Figure 1 Equilibrium diagram of part of the system, FeO-SiO_2-CaO [6].

melting temperature than those generated by aluminum and titanium based lances. Experimental results have shown that chemical modification of the iron based thermal lance (Hot-Kizz^{TM} [9]) improved lance piercing performance.

2. Eutectic generation effect by metal oxides in concrete cutting process

Iron replacement with other metals such as aluminum, titanium and magnesium is one of the major modifications of the thermal lance. The adiabatic temperatures of combustion of these metal-oxygen systems calculated by the code of Gordon-McBride [10] are listed in Table I.

Table I shows that aluminum and titanium have substantially higher adiabatic temperatures than iron. The adiabatic temperature of magnesium is comparable to that of iron. Therefore, it is possible to increase the lance temperature by replacing iron with aluminum and/or titanium. Using magnesium would not cause a substantial lance temperature increase.

TABLE I Adiabatic temperature of metal-oxygen combustion system

Reaction	Input T (K)	Output T (K) adiabatic temperature
$2Fe + O_2 = 2FeO$	298	3325
$4Al + 3O_2 = 2Al_2O_3$	298	3964
$2Mg + O_2 = 2MgO$	298	3393
$Ti + O_2 = TiO_2$	298	3929

However, in the concrete cutting process, lance temperature is not the only factor that affects the cutting performance. Another key factor is the eutectic generation effect of the metal oxides. Eutectic generation effect is the decrease of lava temperature by adding metal oxide to the lava [11]. In a system of multi components, the melting temperature of the system can be lower than the melting temperature of each component because the eutectic mixture is generated.

The metal oxides (MO_x) supplied by the lance form melting lava together with the concrete components during the cutting. The lava can be considered as a ternary system of MO_x-SiO_2-CaO assuming the major components of the concrete are SiO_2 and CaO. The SiO_2-CaO (lava) melting temperature can be decreased by adding a third component, MO_x. The lower melting temperature the lava has, the easier its removal. The cutting/piercing rate is mostly determined by the lava removal speed. Malier [11] reports that when an iron lance is used for concrete, the reaction system of the FeO-SiO_2-CaO obtains a relatively low melting point in the 1100 to 1300°C range. In the phase diagram of SiO_2-CaO system [12], the lowest eutectic point of the system is above 1400°C. Therefore, adding FeO to the SiO_2-CaO system significantly decreases the melting point of the system. The ternary phase diagram of FeO-SiO_2-CaO system [6] is shown in Fig. 1.

The concrete can be considered approximately as a mixture of cements (CaO + SiO_2), sand (SiO_2) and coarse aggregates. The weight percentage of SiO_2 in different cements varies from 25 to 29% [13]. To make a simple estimate of the SiO_2 weight percentage in the

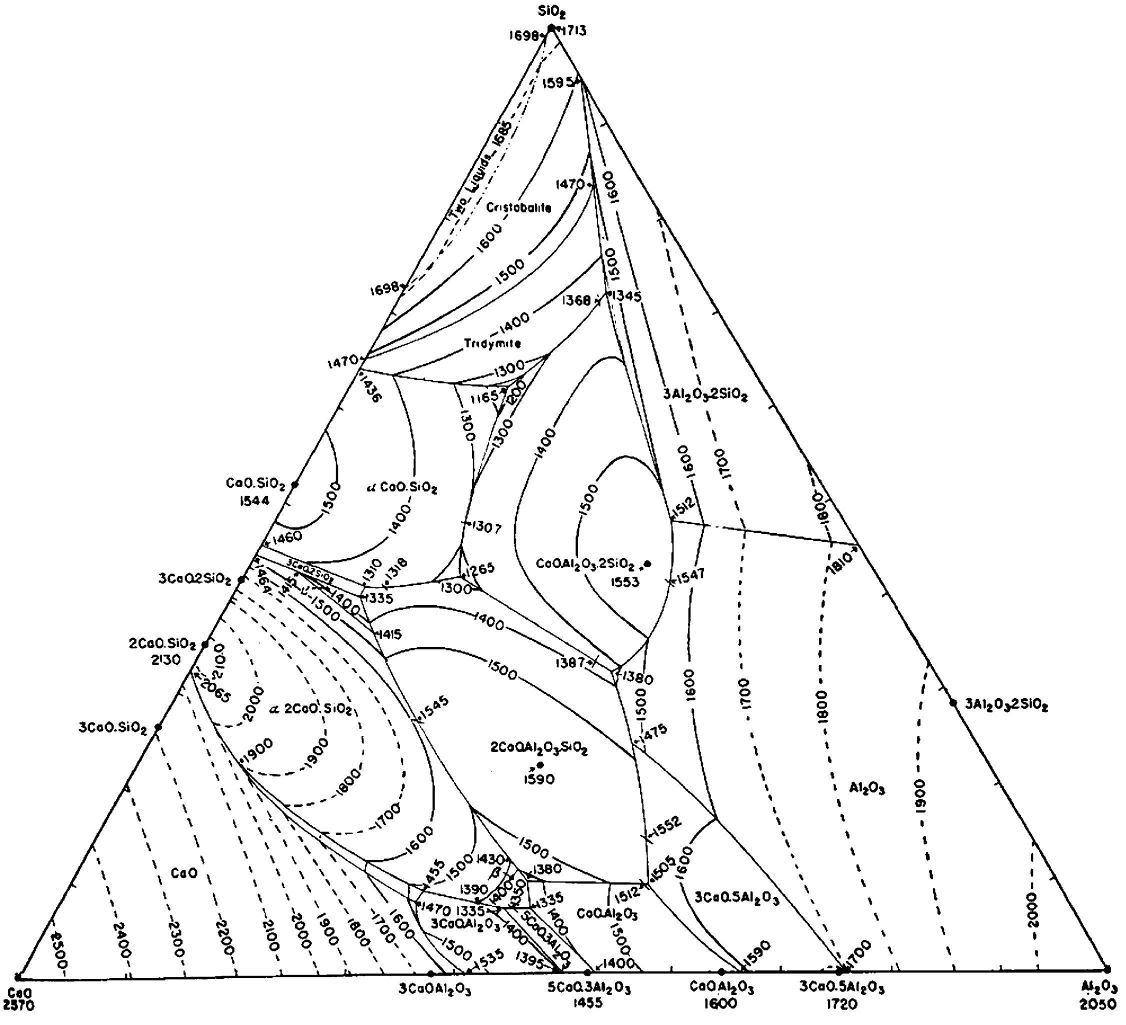

Figure 2 Equilibrium diagram of the system Al_2O_3-SiO_2-CaO [8].

concrete, we used the composition of cement type I (25.8% SiO_2) [13]. The sand and cement weight ratio for field use concrete is about 2:1 [13]. It is difficult to predict the chemical compositions of the aggregates. To simplify the case studied, we considered the concrete made of sand and cement (2:1) only. We applied the same rule for the experiment concrete samples we made. Based on the compositions given above, the calculated SiO_2weight percentage of the concrete made by sand and cement type I is about 78%. Since concrete is such a complicated mixture, the SiO_2 weight percentage can vary greatly from 50 to 90%.

The FeO-SiO_2-CaO diagram in Fig. 1 reveals the existence of a thermal valley that shows relatively low melting point and the valley is rather wide to cover the weight percentage variation range of concrete (50–90%). The two solid arrows in the diagram describe the lava melting temperature change when iron oxide from the burning lance is added. Fig. 1 shows that the melting temperature of FeO-SiO_2-CaO system decreases as the FeO concentration increases for fixed SiO_2-CaO ratio (along the direction of the solid arrows). This explains why the wire core lance is more efficient than the prototype lance [2]. The prototype lance was made with centered iron tube(s). The linear density of the lance is lower than that of the iron wire core lance. The reaction of iron is a surface reaction [14]. Therefore, there is not a substantial difference between the burning rates (m/s) of both types of lances. Assuming the burning rates of two types of lances are the same, iron core lances provide more iron oxide to the concrete than the prototype lance because it has a higher linear density. The melting temperature of FeO-SiO_2-CaO system for an iron core lance can be as low as 1100°C.

As aluminum and titanium can provide higher lance temperatures, the eutectic generation effect of Al_2O_3 and TiO_2 is investigated. The ternary phase diagrams of Al_2O_3-SiO_2-CaO [8] and TiO_2-SiO_2-CaO [7] are given in Figs 2 and 3 respectively.

In Figs 2 and 3 there is not a thermal valley that has both relatively low melting temperature and a wide composition range. In the ternary system of Al_2O_3-SiO_2-CaO, several thermal valleys can be found. However, these valleys are narrow, which means they are difficult to be reached without extremely precise proportioning of the three components. Since thermal cutting is a crude method, extremely precise proportioning is impossible. Most of the invariant points (the lowest theoretical melting temperature) in the thermal valley center are above 1300°C. When a large amount of Al_2O_3 is added to the system at low cutting/piercing rate, the system's melting temperature increases substantially.

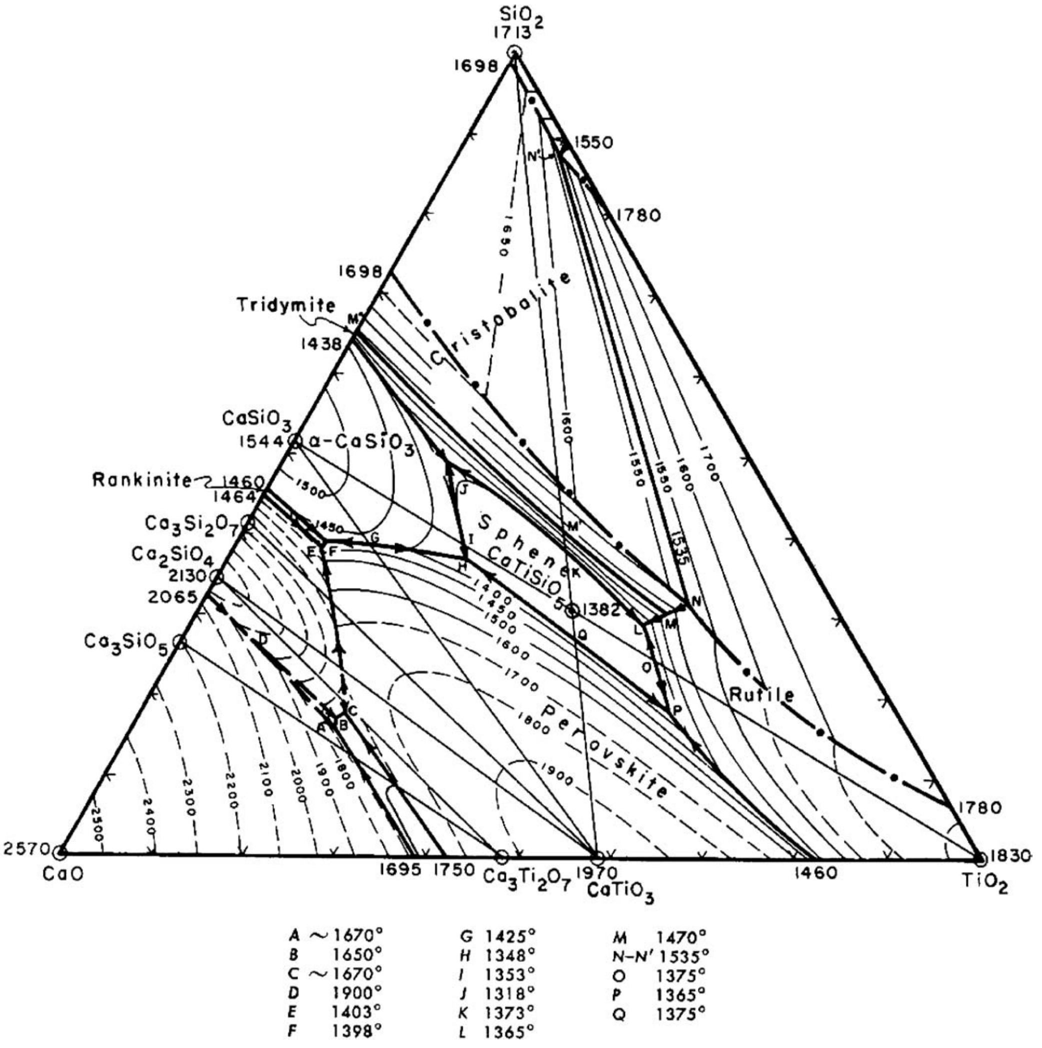

Figure 3 Proposed phase equilibrium diagram for the system TiO_2-SiO_2-CaO. Compositions are in wt%; temperatures in °C. Heavy lines are phase boundaries; fine lines are isotherms (dashes in both cases indicate uncertainty). Heavy dash-dot lines indicate boundaries of two-liquid region. Letters refer to invariant points listed [7].

This makes the cutting/piercing more difficult. Therefore, introducing Al_2O_3 to the SiO_2-CaO system cannot decrease the system's melting point in general.

Adding TiO_2 has the similar effect as adding Al_2O_3. In the ternary system of TiO_2-SiO_2-CaO, all of the invariant points (A to Q) listed in the diagram are above 1400°C or close to 1400°C. The thermal valleys are relatively wide, but the melting temperatures are generally high. The system's melting temperature also increases substantially when large amount of TiO_2 is added at low cutting/piercing rate. The cutting/piercing becomes more difficult.

To summarize, it can be stated that replacing iron by aluminum or titanium may increase the lance temperature. However, this improvement is offset by the increased melting temperature of the systems. Penetration experiments of the iron wire core lance and titanium/aluminum modified lances proved this fact. The penetration rate of the iron wire core lance was about 0.1–0.15 cm/s. When titanium and aluminum modified lances were used, it was impossible to make a hole after the entire lance had been consumed. The experimental results have shown that the increased lance temperature was not able to offset the increased lava melting point. The iron lance performs best.

3. Chemical modification of iron based lance

The commercially available iron based thermal lance (CAL) was chosen for further modification because it outperformed the other two types made by titanium and aluminum.

In our modification, a solid fluorine compound was applied to the lance [9]. The fluorine compound is able to convert SiO_2 to volatile SiF_4 and remove it from the system [15]. Therefore, the total amount of lava is reduced, and the piercing rate is increased.

The fluorine modified lance (Outer diameter—3/8″ (0.953 cm) developed by Ceramic and Materials Processing, Inc., Hot-Kizz^{TM}) was compared with the commercially available lance (Outer diameter—3/8″ (0.953 cm), CAL). Experiments were performed with different concrete block thicknesses at different oxygen pressures (50 PSI (3.45×10^5 Pa), and 80 PSI (5.52×10^5 Pa).

The concrete blocks were made by one part of commercial cement and two parts of sand. The block composition was semi-quantitatively analyzed using the following chemical method. The concrete sample was delivered to excessive amount of hot concentrated HCl solution. Minerals except SiO_2 were all dissolved into the liquid solution. This solution was filtered.

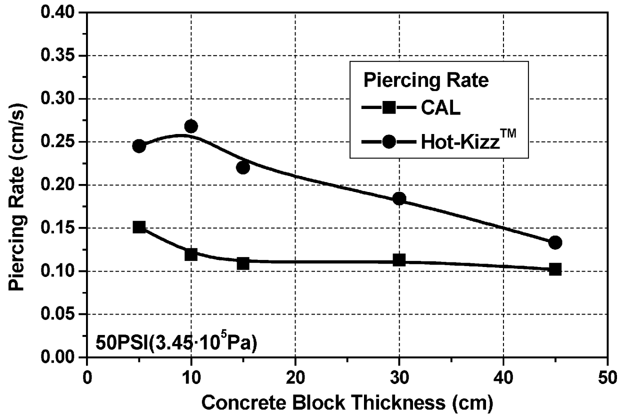

Figure 4 Performance comparison between commercial available lance (CAL) and Hot-Kizz™ under 50 PSI (3.45×10^5 Pa).

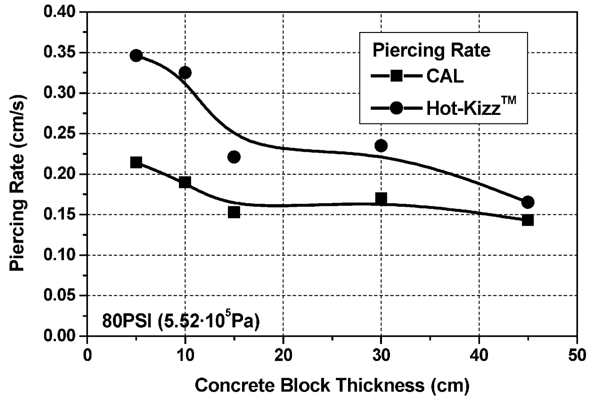

Figure 5 Performance comparison between commercially available lance (CAL) and Hot-Kizz™ under 80 PSI (5.52×10^5 Pa).

The weight of un-dissolved mass was measured as the weight of SiO_2. The calcium in the filtered solution is precipitated by adding NaC_2O_4 solution into it. The precipitation (CaC_2O_4) was filtered and dried. Its weight was measured. The semi-quantitative chemical analysis showed the concrete block had about 77% of SiO_2.

Different from mechanical cutting methods, thermal lance cutting was not influence by concrete strength. The target is melt out no matter how strong it is. On the contrary, thermal lance cuts fast in reinforced concrete because the reinforcement acts as additional fuel which increases the flame temperature. This is another advantage of using thermal lance cutting.

Figs 4 and 5 show that Hot-Kizz™ has a higher piercing rate than the commercially available lance at both 50 PSI (3.45×10^5 Pa) and 80 PSI (5.52×10^5 Pa) in each piercing concrete thickness.

In order to evaluate the piercing rate of the commercially available lance (CAL) and the Hot-Kizz™ lance, we introduced the parameter, Relative Piercing Rate Index (RPRI) defined below:

$$\mathrm{RPRI} = \frac{\mathrm{PiercingRate}_{\mathrm{Hot\text{-}Kizz}} - \mathrm{PiercingRate}_{\mathrm{CAL}}}{\mathrm{PiercingRate}_{\mathrm{CAL}}}$$

Fig. 6 shows that when the concrete block is relatively thin, the RPRI is as high as 1.2 at 50 PSI (3.45×10^5 Pa) and 0.7 at 80 PSI (5.52×10^5 Pa). With increasing block thickness, the RPRI decreases.

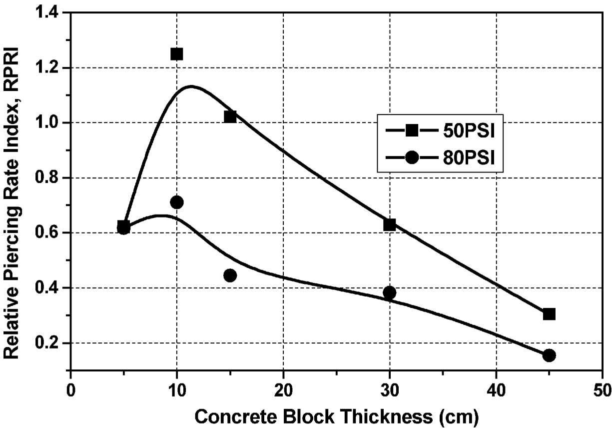

Figure 6 RPRI at 50 PSI (3.45×10^5 Pa) and 80 PSI (5.52×10^5 Pa).

4. Discussion

The explanation of improved performance of Hot-Kizz™ is based on partial lava gasification. As part of the lava volatilizes from the system, the amount of lava to be removed is reduced. This effect has improved the piercing rate. Another improvement is that the modification also decreased the melting temperature of the lava. The fluorine modification can only remove SiO_2 from the system [15]. CaO stays in the system. This decreased the weight ratio of SiO_2 to CaO. From the ternary phase diagram of FeO-SiO_2-CaO (Fig. 1), this fact can be understood as the solid arrow shifts down to the CaO side (dash line). If the initial SiO_2 weight percentage is above 65%, which is usually true, decreasing the SiO_2 percentage in the system decreases the system melting temperature more quickly than adding more FeO to the system.

If the concrete block thickness is around 10 cm, the performance improvement is obvious. However, with increasing concrete thickness the problems with the remaining liquid lava obstructing its removal increase.

When the oxygen pressure is increased from 50 PSI (3.45×10^5 Pa) to 80 PSI (5.52×10^5 Pa), the RPRI decreases. It is obvious that higher oxygen flow increases the lava removal; therefore, the difference of the piercing rate between Hot-Kizz™ and the commercially available lance (CAL) becomes less obvious.

5. Conclusions

1. The analysis of eutectic generation effect shows that the iron-based thermal lance outperforms titanium and aluminum modified thermal lances, although these two lances have higher lance temperatures.

2. The chemically modified thermal lance, Hot-Kizz™ (Ceramic and Materials Processing, Inc.), improved the lance piercing performance up to two times when compared with the commercially available lance.

3. The improvement of chemically modified lances can be explained by two effects: partial lava gasification and lava melting temperature decrease due to SiO_2 removal.

Acknowledgement

UB Foundation of SUNY at Buffalo acknowledges the financial support and material assistance from Ceramic and Materials Processing, Inc.

References

1. E. BRANDENBURGER, *Metal Constr.* (1975) 617.
2. G. SZYCHLINSKI, *Concr. Intern.* (October 1985) 51.
3. I. L. DAVIES, C. C. FLEISCHER and A. A. PATON, *Nucl. Eng. Intern.* **32** (1987) 45.
4. J. S. BROWER, "Underwater Cutting Rod," U.S. Patent 4,069,407 (1978).
5. J. S. BROWER, "Underwater Cutting Rod," U.S. Patent 4,182,947 1980.
6. N. L. BOWEN, J. F. SCHAIRER and E. POSNJAK, *Amer. J. Sci.* **XXVI** (1933) 192.
7. R. C. DEVRIES, R. ROY and E. F. OSBORN, *J. Amer. Ceram. Soc.* **38** (1955) 158.
8. J. F. SCHAIRER, *ibid.* **25** (1942) 241.
9. V. HLAVACEK and P. PRANDA, "High-Speed Chemical Drill," U.S. Patent Application.
10. S. GORDON and B. J. MCBRIDE, *NASA Refer. Publ.* (1996) 1311.
11. Y. MALIER, in 2nd RILEM International Symposium on Demolition and Reuse of Concrete and Masonry (Chapman and Hall, London, 1988) Vol. 1, p. 236.
12. N. A. TOROPOV, V. P. BARZAKOVSKII, V. V. LAPIN and N. N. KURTSEVA, "Handbook of Phase Diagrams of Silicate" (Israel Program for Scientific Translations, Jerusalem, 1972).
13. REA Staff of Research and Education Association, "Handbook of Concrete Technology and Masonry Construction" (The Association, New York, 1981).
14. D. B. WILSON, T. A. STEINBERG and J. M. STOLTZFUS, "Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres" (ASTM, West Conshohocken, 1997) p. 240.
15. H. WANG, P. PRANDA and V. HLAVACEK, *accepted by Chemical Engineering Communications*.

Received 25 September 2003
and accepted 3 June 2004