MELT/CONCRETE INTERFACE TEMPERATURE RELEVANT TO MCCI PROCESS

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ABSTRACT

The goal of the current large-scale MOCKA tests is to gain insights about a 2-dim concrete erosion process by an oxide and metal melt in a stratified configuration, which is the most probable late phase configuration, in cylindrical concrete crucibles without and with 12 wt.% of reinforcing steel. To allow for longer-term MCCI a new method of melt heating was implemented to simulate the decay heat. Dedicated exothermal chemical reactions are used to achieve a prototypic heating of both melt phases. Electrical circuits with in concrete embedded electrodes have shown a considerable delay of the arrival of the metal melt if compared to the failure time of the K-Type thermocouples at approx. 1370 °C. In addition, an examination of the melt/concrete interface after the section of the concrete crucible has revealed the melting of the reinforcing steel during the MCCI process. This should result in higher melt pool temperatures than during MCCI with concrete without reinforcement for which previously a concrete decomposition temperature of approximately 1300 °C was estimated. Surprisingly, a similar long-term melt temperatures and pretty much the same eroded concrete volumes have been also found in MOCKA experiments without rebars. As the thermal properties of the pure concrete and that of the reinforced concrete do not differ much and, in addition, a much the same internal heating power was generated in all experiments under, the former estimated decomposition temperature of the pure concrete cannot be used to prescribe the temperature boundary condition for the MCCI process.

KEYWORDS:
MCCI, MOCKA experiments, reinforced concrete, melt/concrete interface temperature

1. INTRODUCTION

The composition of the concrete seems to influence the interaction of melt with concrete. Concrete is a complex mixture of cement, water and aggregates which for most plants consists of variable proportions of silica (SiO₂) and limestone (CaCO₃). Depending on the SiO₂/CaCO₃ ratio the concrete used in nuclear power plants can be divided into three categories, namely siliceous, LCS and pure limestone. For a concrete with limestone aggregates, lime burning, i.e. the thermal decomposition of CaCO₃ to CaO and CO₂ above approx. 780 °C [1], may increase the amount of released gases by a factor 3 in comparison with siliceous concrete. An important issue concerns the distribution of the heat flux to the concrete in the lateral and axial directions during the long-term 2-dimensional concrete erosion by a prototypic core melt. The knowledge of the distribution of the heat flux to the concrete in the lateral and axial directions during the long-term concrete erosion is important for the evaluation of the consequences of a severe reactor accident [2], [3]. Axial erosion can penetrate the reactor basemat, while lateral erosion can destroy containment structures.
The BETA and the COMET-L test series ([4], [5] and [6]) provided valuable data on two-dimensional metallic core concrete interaction under dry conditions with decay heat simulation of intermediate power, and subsequently at reduced power. First experiments with prototypic oxide corium melts with sustained heating were performed only in one-dimensional crucibles ([7], [8]).

The CCI tests [9], [10] investigated the long-term interaction of a heated (direct electrical heating) oxide core melt within rectangular LCS and siliceous concrete crucibles. The initial crust, which formed at the oxide/concrete interface in all experiments, were not appreciably heated by the used heating system. Different failure modes of this initial crust lead to irregular cavity shapes in the CCI-1 and CCI-3 tests with siliceous concrete [11]. The high gas release rates from the decomposing LCS concrete can help to destabilize these initial crusts as observed in the CCI-2 experiment. After approx. 40 min after completion of the thermite reaction only the initial bottom crust failed. The lateral crusts disappeared somewhat later, however, the final shape of the concrete cavity was rather symmetrical.

Recently, a series of large-scale MOCKA (Metal Oxide Concrete Interaction in Karlsruhe) experiments studied the interaction of a simulant oxide and metal melt in a stratified configuration with siliceous, LCS and basaltic concrete. The program was focused on assessing the influence of a typical 12 wt% reinforcement in the concrete on the erosion behavior. The developed method of using the heat of chemical reactions to simulate the decay heat generates a rather prototypic heating of both melt phases.

2. MOCKA EXPERIMENTS

In all MOCKA experiments concrete crucibles with an inner diameter of 25 cm are used. Both the sidewall and basemat are instrumented with Type K thermocouple assemblies to approximately determine the position of the progressing melt front into the concrete as well as tungsten-rhenium thermocouples for measuring the melt temperatures. A total of 63 thermocouples are implemented. The initial melt consists of 42 kg Fe, overlaid by 68 kg oxide melt (initially 56 wt.% Al₂O₃, 44 wt.% CaO). The collapsed height of the metal melt is about 13 cm and that of the oxide melt 50 cm. The initial melt temperature at start of interaction is approximately 1840 °C. The CaO admixture lowers the solidus temperature and the viscosity of the oxide melt. The resulting solidus temperature of approx. 1360 °C is sufficiently low to prevent a formation of an initial crust at the oxide/concrete interface, which was observed in the CCI experiments, [9], [10], [11], [12]. The oxide/concrete interface contact temperature in MOCKA tests was estimated to be 1400 °C. After the completion of the thermite burn, thermite and Zr was added to the melt within approximately 40 minutes. The heat generated by the thermite reaction and the exothermal oxidation reaction of Zr is mainly deposited in the oxide phase. Due to density-driven phase segregation the metal melt at the bottom of the crucible is fed by the enthalpy of the steel which is generated in the oxide phase by the thermite reaction of the added thermite. Taking the reaction enthalpies of the added Zr and thermite into account, approximately 73 % of the heating power is deposited in the oxide phase and 27 % in the metal melt.

2.1 MCCI on Siliceous Concrete without Rebars

The post-test cavity erosion profile of the MOCKA 5.4 test, Figure 1, shows a maximum downward erosion of 90 mm and a maximum sideward ablation of 110 mm by the metal melt and 100 mm by the oxide melt. The eroded concrete volume by the oxide melt and by the metallic melt were estimated to 0.0513 m³ and 0.021 m³, respectively. The total heating power was approximately 428 kW in the oxide phase and 159 kW in the metallic melt.
Figure 1. Section of the MOCKA 5.4 concrete crucible with an indication of the initial size of the crucible cavity (blue line). The orange line indicates the initial height (13 cm) of the metal melt and the red line marks the outer surface of the cylindrical crucible.

Pretty much the same results were obtained the MOCKA 5.3 test, Figure 2. The generated heating power was 450 kW and 168 kW in the oxide melt and the metal melt, respectively. 0.057 m³ of concrete was eroded by the oxide and 0.022 m³ by the metal melt.

Figure 2. Section of the MOCKA 5.3 concrete crucible with an indication of the initial size of the crucible. The orange line indicates the initial height (13 cm) of the metal melt and the red line marks the outer surface of the cylindrical crucible.
2.2 MCCI on Siliceous Concrete with Rebars

The post-test cavity erosion profiles of the MOCKA 5.6, MOCKA 5.7 and MOCKA 5.8 tests with reinforced concrete are shown in Figure 3 to Figure 5. The content of the reinforcing steel was approximately 12 wt.%. The rebar structure is depicted in Figure 6. The diameter of the steel bars used in all MOCKA experiments is 8 mm. The total heating power was approximately 438 kW, 446 kW, 438 kW in the oxide phase and 159 kW, 160 kW, 159 kW in the metallic melt, which resulted in an erosion of 0.039 m³, 0.035 m³, 0.033 m³ of concrete by the oxide and 0.018 m³, 0.019 m³, 0.020 m³ by the metallic melt in MOCKA 5.6, MOCKA 5.7 and MOCKA 5.8, respectively.

Figure 3. Section of the MOCKA 5.6 concrete crucible with an indication of the initial size of the crucible cavity (blue line). The orange line indicates the initial height (13 cm) of the metal melt and the red line marks the outer surface of the reinforced siliceous cylindrical crucible.
Figure 4. Section of MOCKA 5.7 concrete crucible with an indication of the initial size of the crucible cavity (blue line). The orange line indicates the initial height (13 cm) of the metal melt and the red line marks the outer surface of the reinforced siliceous cylindrical crucible.

Figure 5. Section of the MOCKA 5.8 concrete crucible with an indication of the initial size of the crucible cavity (blue line). The orange line indicates the initial height (13 cm) of the metal melt and the red line marks the outer surface of the reinforced siliceous cylindrical crucible.
2.3 Melt/Concrete Temperature relevant to MCCI Process

The examination of the melt/concrete interface after the section of the concrete crucible, Figure 7 to Figure 9, has revealed the melting of the reinforcing steel during the MCCI process. No indications of an enhanced oxidation of the rebars have been found. Therefore, the rebars in the concrete elevates the melt/concrete interface temperature up to the melting temperature of the reinforcing steel, i.e. 1526 °C. This should result in much higher melt pool temperatures than during MCCI with concrete without reinforcement for which previously so called concrete decomposition temperature of approximately 1300 °C was estimated. Surprisingly, a comparably high long-term temperature was also found in MOCKA experiment on siliceous concrete without rebars. In all CCI experiments on siliceous concrete without rebars ([10], [11], [12]) the temperature of the oxide melt clusters around 1650 °C. The same quasi-stationary temperature of the oxide melt was also measured in MOCKA 5.4 test, Figure 10. As the thermal properties, i.e. the decomposition enthalpy and the specific heat capacity which were estimated using the mixing rule for the reinforced concrete do not differ much from these of pure concrete and, in addition, a very much the same internal heating power was generated in all experiments under consideration, the former estimated decomposition temperature of the pure concrete of approximately 1300 °C cannot be used to prescribe the temperature boundary condition for the MCCI process. The analysis of the temperature data obtained from K-Typ thermocouples embedded in a concrete crucible without rebars (Figure 11) and a crucible with rebars (Figure 12) does not show a more pronounced heat-up of the reinforced concrete ahead the moving melt front, therefore, there is no enhanced heat transfer in the concrete by heat conduction due to the rebars.
Figure 7. Melting of the reinforcing steel at the oxide melt/concrete interface.

Figure 8. Rebars at the oxide melt/concrete interface.
2.4 Theoretical considerations

Let consider a MCCI configurations:

\[
(m_0, T_0, c_p, c_p^B, \rho, \rho_B, f_{H_2O,CO_2}, f_{rebar}, T_{int}, H_{dec}, P_h, \alpha, S_{0_B}, S_{0_rad})
\]

where \(m\) is the mass of the melt, \(\rho\) the density and \(T_0\) the initial temperature of the melt. \(c_p\) is a modified specific heat capacity which includes the phase transition enthalpy. \(c_p^B\) is the specific heat capacity and \(\rho_B\) the density of the concrete. \(f_{H_2O,CO_2}\) is the mass fraction of the \(H_2O\) and \(CO_2\) and \(f_{rebar}\) the mass fraction of the reinforcing steel in the concrete. \(T_{int}\) is the melt/concrete interface temperature which governs the MCCI process and \(H_{dec} = H_{dec}(T_{int})\) the decomposition enthalpy of the concrete. \(P_h\) is the decay heat. \(S_B\) is the contact surface of the melt with concrete and \(S_{rad}\) is the upper surface of the melt. The heat flux from the melt to the concrete is described by the heat transfer coefficient \(\alpha\).

The following discrete balance equation holds for the MCCI process:

\[
\begin{align*}
\dot{Q}_B(t_k)S_B(t_k) + \dot{Q}_{rad}(t_k)S_{rad}(t_k) + \dot{Q}_{cond}(t_k)S_B(t_k) - P_h \Delta t_k \\
+ \Delta m_B(t_k)c_p^B[T(t_{k+1}) - T_{int}] \\
= m(t_k)c_p(t_k)[T(t_k) - T(t_{k+1})],
\end{align*}
\]

\(t_k\) is the time coordinate and \(\Delta t_k = t_{k+1} - t_k, k = 0, 1, ...\)

\(\dot{Q}_B(t_k) = \alpha[T(t_k) - T_{int}]\) is the heat flux to the concrete.
\( \dot{Q}_{\text{rad}}(t_k) \) and \( \dot{Q}_{\text{cond}}(t_k) \)

are the heat fluxes due to radiation and heat conduction to the concrete, respectively.

\[ \Delta m_B(t_k) = \dot{Q}_B(t_k) S_B(t_k) \Delta t_k / H_{\text{dec}} \]

is the eroded mass of concrete.

\[ m(t_k) = m(t_{k-1}) + (1 - f_{\text{H}_2\text{O},\text{CO}_2}) \Delta m_B(t_{k-1}), \]

\[ c_p(t_k) = \frac{1}{m(t_k)} \left[ m(t_{k-1}) c_p(t_{k-1}) + (1 - f_{\text{H}_2\text{O},\text{CO}_2}) \Delta m_B(t_{k-1}) c_p^B \right], \quad k \geq 1. \]

For \( k = 0 \):

\[ m(t_0) = m_0, \]

\[ c_p(t_0) = c_p, \]

\[ T(t_0) = T_0. \]

Using algebraic manipulations Eq.(2) yields:

\[ T(t_{k+1}) = T(t_k) - \{ \alpha S_B(t_k)[T(t_k) - T_{\text{int}}]\Delta t_k - [P_h - P_{\text{loss}}(t_k)] \Delta t_k - \Delta m_B(t_k) c_p^B [T(t_k) - T_{\text{int}}] \} / [m(t_k) c_p(t_k) + \Delta m_B(t_k) c_p^B] \]  

\[ (3) \]

where

\[ P_{\text{loss}}(t_k) = \dot{Q}_{\text{rad}}(t_k) S_{\text{rad}}(t_k) + \dot{Q}_{\text{cond}}(t_k) S_B(t_k). \]

For all \( t_k \geq t_{\text{qs}} \), i.e. within the quasi-stationary time period the following equation holds:

\[ P_{\text{er}}(t_k) \Delta t_k - \{(P_h - P_{\text{loss}}(t_k)) \Delta t_k - \Delta m_B(t_k) c_p^B (T(t_k) - T_{\text{int}}) \} = 0, \]  

\[ (4) \]

\( P_{\text{er}}(t_k) \) is the power which is transferred to the concrete.

\( P_{\text{er}}(t_k) \) can be approximated from the estimated volume of eroded concrete, \( V_{\text{er}}(t_{\text{exp,end}}) \), in the experiments under consideration, i.e.:

\[ P_{\text{er}}(t_k) \approx \rho_B V_{\text{er}}(t_{\text{exp,end}}) H_{\text{dec}}(T_{\text{int}})/t_{\text{exp,end}} \quad \text{for all} \quad t_k \geq t_{\text{qs}} \]  

\[ (5) \]

where \( t_{\text{exp,end}} \) denotes the end of the heating time.

Using the quasi-stationary approximation (Eq. 4) together with Eq. (5) and \( T_{\text{int}} = T_{\text{Liq( rebars)}} = 1526 \degree \text{C} \)

the solution of Eq.(3) provides a good agreement with the melt temperatures measured in MOCKA 5.6 and MOCKA 5.7 experiments (Figure 10) for \( \alpha = 1100 \text{W/(m}^2\text{K)} \). The performed uncertainty and sensitivity analysis in [13] supports the use of the above assumption concerning the interface temperature \( T_{\text{int}} \). It is obvious that the above estimated heat transfer coefficient can be used for the analysis of the MOCKA 5.4 experiment which was performed using the same melt and concrete, except the rebar structure. For \( T_{\text{int}} = 1500 \degree \text{C} \) the solution of Eq.(3) together with Eq.(4) and Eq.(5) reproduces the measured temperature data very well (Figure 10). In contrast to the MOCKA tests with siliceous concrete, in all MOCKA experiments on LCS concrete with and without rebars almost the same results, i.e. melt temperatures and the volumes of eroded concrete were obtained [14], consequently, the melt/concrete interface temperature, \( T_{\text{int}} \), which is relevant to the MCCl process of the pure LCS concrete must the same as for a reinforced concrete, i.e. in the range of the melting temperature of the commonly used reinforcing steel, i.e. approximately 1526 \degree \text{C}. The heat transfer coefficient between the oxide melt and LCS concrete
was estimated as high as $\alpha = 4000 \, \text{W/(m}^2\text{K)}$, which is considerably higher than that estimated in MOCKA experiment with siliceous concrete.

Figure 10. MOCKA oxide melt temperatures.

Figure 11. Lateral wall heat up ahead the moving front of the oxide melt (black circles) in pure concrete.
3. CONCLUSIONS

The rebars in the concrete elevates the melt/concrete interface temperature up to the melting temperature of the reinforcing steel, i.e. 1526 °C. However, a pretty much the same long-term temperature was also found in tests with concrete without rebars, consequently, the previously estimated concrete melting temperature of about 1300 °C cannot be considered as a melt/concrete boundary temperature which governs the MCCI process. Using the experimental results a quasi-stationary approximation of the energy balance equation has been used to estimate the concrete/melt temperature relevant to the MCCI process in MOCKA test with pure siliceous concrete. This temperature was estimated to be approximately 1500 °C. An experimental program to investigate the concrete decomposition process at high temperatures has been designed.

In contrast to an anisotropic concrete ablation caused by an unpredictable failure of the initially formed melt crusts, which are not appreciably heated by the used heating methods, in CCI-1 (very much pronounced one-sided lateral ablation), CCI-3 (pronounced two-sided lateral ablation) and CCI-5 (175 min of downward concrete erosion with subsequent lateral ablation of the considerably preheated concrete) experiments, a rather isotropic ablation was obtained in all MOCKA tests on siliceous concrete with and without rebars.

In all performed MOCKA experiments on LCS concrete very much the same results have been obtained for concrete with and without rebars. The overall downward erosion by the metal melt was much less due to the formed bottom crust than the sideward one. The lateral concrete erosion by the overlaid oxide melt was about the same as that of the metal melt. Different cavity erosion was observed in the CCI-2 and CCI-4 tests on LCS concrete. In CCI-2 after the initial downward concrete erosion, the subsequent lateral ablation has led to a rather symmetrical final shape of the concrete cavity. Whereas in test CCI-4 an axially pronounced final cavity erosion profile was obtained. It should be stressed that the knowledge of the relation between the axial and lateral basemat erosion is important in evaluation of the consequences of a severe reactor accident. The performed small- to large-scale experiments have encountered a variety of phenomena of MCCI behavior. However, it is by no means clear which of these observed phenomena...
will occur in a MCCI process at the reactor scale. In addition, the obtained results need careful interpretation for application to the reactor accident, as the analysis of the MCCI at the reactor scale still requires extrapolation beyond the existing experimental database.

4. REFERENCES


