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HW/8

Study of heat-mass transfer in reactor containment wall

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ABSTRACT

When exposed to loss of coolant accident (LOCA) conditions, water in the concrete of reactor containment wall vaporises and a migration of water through the concrete under thermal and pressure gradients occurs. In this paper the behaviour of concrete (ordinary and high performance) is discussed. Test equipment representing a reactor containment wall subjected to hygrothermal loading is presented. Experiments are carried out on a concrete cylinder (Φ50x130 cm) and its temperature, pore pressure, water content and leak rate are measured. The results of a numerical model are also presented.

INTRODUCTION

This paper concerns the hygrothermal consequences following a loss of coolant accident (LOCA), on a prestressed concrete containment vessel. The objective is to study how the wall, without cracks, prevents the escape of radioactive fission products to the outside environment. In this study, the wall thickness considered is 1.3 m, with a high performance concrete [1], with and without a composite liner of 3 mm thick. Practically, two levels of accidental conditions are considered:

- The design accident conditions (LOCA) consist of a rise from ambient conditions to a dew point of 160°C and a pressure of 650 KPa. This rise is followed by a cooling which reaches approximately 200 KPa and 120 °C in 12 to 24 hours. This level is then maintained practically constant during several days.
- The case of severe accident conditions (SA conditions), consist of a rise from ambient conditions to a dew point of 200°C and a pressure of 1000 to 1500 KPa. These conditions are maintained during 24 hours before cooling (figures 1 and 2).

When the containment vessel is loaded by temperature and vapour pressure, the water in the concrete will vaporise and a migration of water through the concrete under thermal and pressure gradients occurs. In the case of the containment with a composite liner, if the pore pressure in the concrete is higher than the pressure due to LOCA or SA conditions the liner adhesion may fail which may lead to a loss of leak tightness of the composite liner. Therefore, it is essential to estimate the evolution of the pore vapour pressure in concrete during the accident period.

On the other hand, in the case of a containment vessel without a composite liner there are some differences due to the entrance of vapour into the concrete under pressure. In this case, it is important to study whether the leak tightness could be further improved by plugging the pores by the liquid phase.

In both cases, it is necessary to compare numerical results with physical observations as completely as possible and to take into account the specifications of a HPC with reduced capillary porosity. For this purpose a test equipment presented hereafter has been developed to permit the simulation of the studied accidental conditions, allowing the measurement of temperature, pressure and water content in the concrete specimen.

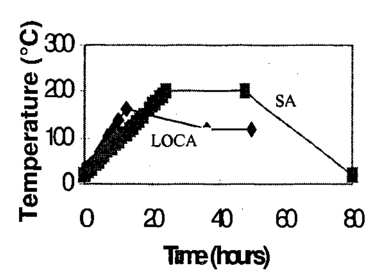

Figure 1: Temperature variation in the heated chamber

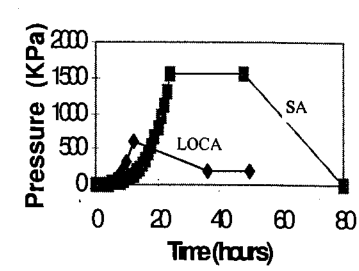

Figure 2: Pressure variation in the heated chamber

1- CONCRETE BEHAVIOUR UNDER LOCA CONDITIONS

The hardened concrete contains free and bound water. Exposed to temperature, a gradual migration of the evaporable water initially present.at room temperature occurs in concrete. Part of this free water will exit from the specimen. Moreover a release of chemically bound water can be produced. Such changes are due to the chemical reactions of dehydration of hardened cement paste and the conversion of calcium hydroxide into calcium oxide. The water being released in this way becomes free water.

It is simple initially to consider that the water phase is the element the most sensitive to temperature variations. This observation has two consequences:

-It puts into relief the importance of the initial moisture state of the concrete (i.e. before the application of thermal loading) which can be characterised by evaporable water content « ω » whose loss would not modify the structure of the material. It should, however, be considered that the release of bound water modifies the physical structure of hydrates, so the value of ω can be only conventional (example: ω can be defined as the evaporable water of the material when it is dried at 105°C until it gets a constant weight).

-The heating of a concrete specimen induces a vaporisation of the water with saturation in the cold part of the specimen, and possibly the development of pressures that are susceptible to induce phase displacements of water in the specimen. These displacements modify the local humidity state and so the properties of the material, particularly its permeability. The rate of heating has noticeable consequences in the observations of these phenomena.

For the accidental condition, mentioned above, structural modifications (the morphology, the nature of hydrates, the porosity and the pore connectivity) of the material are low. This is for three essential reasons: (1) the maximum temperature level remains rather low (200°C); (2) the size of the zone touched by the high temperatures is not large; (3) boundary conditions do not impose significant drying. In fact two major issues concerning thermal effects are significant in the design of nuclear plants. One is the quantification of total pressures obtained in the containment wall and knowledge of the impact of the pressure on the structure. The other one is the need to estimate the leak rate of the wall. These two points have been approached in the literature in different ways:

To measure pore pressure, most of the tests were made with sealed concrete. In this case, a sufficient amount of water is present to maintain a minimum saturated vapour pressure (SVP). Kontani and Shah [2] reported that, at a sustained temperature of 171°C, the maximum pressure measured was 15 to 45% higher than the sum of SVP and PAP (partial air pressure). Their results can be positioned between the maximum and minimum pressures with respect to temperature obtained by England and Khoury in a compilation of pressure test results performed at Imperial College [3] (which are however very sensitive to concrete mix and its constituents). England et al. [4] indicated that after releasing all of the air and some of the water, the pore pressures dropped to SVP. Pore pressures stayed at the SVP until a certain amount of water was further expelled. This indicates that the air contained in concrete may be one reason for the additional pressure on the SVP. Two other reasons for higher pressures than SVP + PAP are proposed by Kontani and Shah. One is that the volume expansion of liquid water is 11% and 20 times larger than that of concrete itself if heated from 21 to 171°C; the other one is the decomposition of admixtures.

Heating a face of a wall causes water migration to occur in both the liquid and vapour phases, and usually leads to zones of physical saturation. The zone of saturation itself migrates under the pressure difference. The pressures in this zone are generally greater than the pore pressures before saturation occurs. With this mechanism and taking into account the permeability of concrete, England and Khoylou [5] explain that the pore pressure in a high performance concrete wall can be higher than those obtained in a normal concrete wall. Indeed in the case of HPC low water/cement ratio and the use of silica fume induce a very narrow pore network which can modify the moisture properties of this type of concrete such as the sorption and desorption isotherms (Barghel-Boury et al.[6]).

Marechal and Ithurrade [7] reported the experiments on the 0.9 meter wall of ordinary concrete under accidental conditions. The authors observed a plugging of the pores by the liquid phase, which reduces the pressure of the porous body downstream of the condensation barrier. Furthermore this barrier moves toward the cold face. Due to formation of this plug zone the results of flow show that the permeability is a lot reduced after the accident. This reduction is dependent upon the initial state of humidity and on the original permeability before the accident. The permeability of a dried specimen can be reduced by a factor of 10 to 20 in an accident, whereas that of an undried specimen can be reduced from 1 to 4 times, and this reduction will be higher if its permeability before the accident is high.

2- STEAM TEST EQUIPMENT

The necessity to have representative dimensions to identify phenomena leads to perform the experimental work on a cylindrical specimen sealed laterally with the same thickness as the reactor containment wall (1,3 m). The choice of diameter for the specimen (0,5 m) has been made taking into account first the effect of the boundary conditions and then the mass to transport. Therefore the experiments are carried out on a concrete cylinder (D=50 and

H=130cm) built according to figure 3. The specimen is positioned vertically and transfers are imposed from the top to the bottom.

2-1- MAIN COMPONENTS

The main components of the test equipment are the following:

1) The frame structure. It is composed by the specimen support resting on three feet, sustaining the whole of the experimental device. A stiff plate at the top is connected to the bottom plate by three steel frames positioned at 120°. An expansion element as shown in figure 3 is provided to avoid differential deformation in the steel frame of the system due to temperature.

2) The sealed and insulated specimen. Internal pressures in the concrete are hold by a cylindrical and metallic envelope (steel casing). The injection of silicon rubber compound of 3 mm thickness between this metallic envelope and the concrete insures the leak tightness laterally. An important lateral thermal insulation completes this setting.

3) The elements of hygrothermal loading. They are realised with the help of a closed chamber positioned directly on the concrete test sample integrating heating elements and a boiler insuring the production of vapour. A regulating system is used to carry out the accidental scenario including temperature and pressure elevation simultaneously.

2-2- MEASURES IN TRANSITORY REGIMES

Considering the large size of specimen in the tests, the establishment of a permanent regime needs to keep the hygrothermal loading constant during a long period, but the duration of accident scenarios is only some days. These are therefore the measures in the transitory regime which are of interest:

1) In the chamber. Measures taken by pressure meter, thermometers and humidity meter positioned in the chamber and in the boiler give the control system the information necessary to follow the temperature and pressure variations (figures 1 and 2).

2) In the specimen. The concrete specimen contains various gauges for temperature, pressure and moisture detection. The position of the different measuring points and different elements of the equipment are shown in figure 3.

The evolution of the pressure, the temperature and the water content as a function of time in the concrete are measured by the pressure tap, the thermocouples and the moisture meters implanted in the specimen at the moment of the casting. The various sensor outputs during the testing process are recorded on a data acquisition board.

The pressure tap consists of a copper pipe having an inside diameter 2 mm and an outside diameter of 4 mm. This pipe is connected with a pressure meter which is placed outside of the specimen. Water content measurements in the concrete specimen is performed by embedded electrical resistance water meters with a volume of 10 cm^3. These consist of a mortar cube (25x20x20 mm) containing two stainless steel drill plates.

The arrangement of the major sensors is diametrical and these are located at the centre of the specimen.

3) At the bottom of the specimen. A system of gas flowmeter, humidity meter and condenser allows separation and quantification of the gaseous part and the liquid part of the outgoing air. It is interesting to note that the plugging of the pores by the liquid phase could be detected both by moisture meters positioned in the specimen and by the gas flowmeter system at the bottom of the specimen.

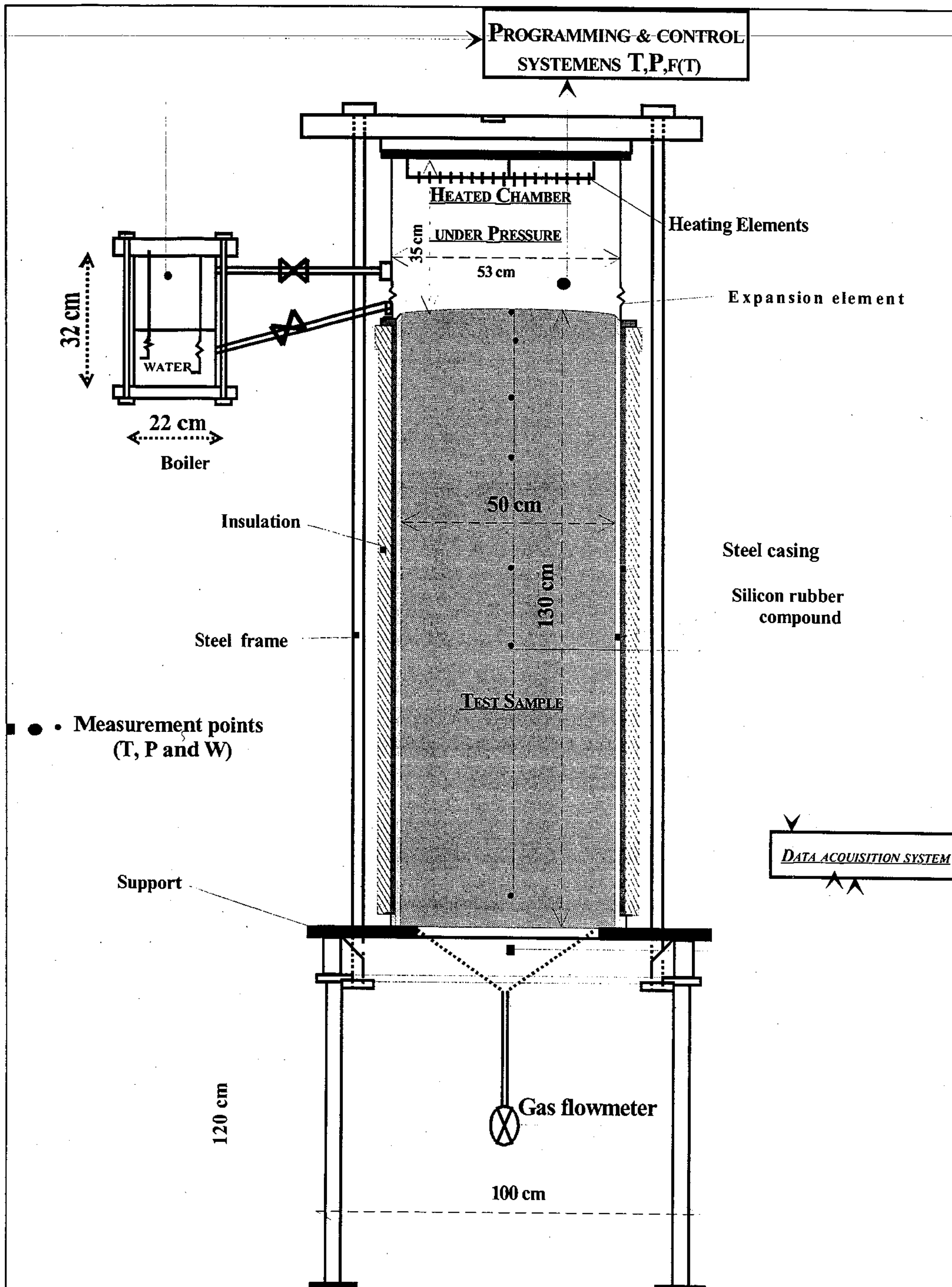

Figure 3: Test set-up

3- NUMERICAL MODEL

The numerical model used in each case should be capable of predicting the major characteristics of the moisture migrational behaviour. For this purpose we intend to start the numerical work by using the TEMPOR2 (1-D) program developed by Bazant et al. [8]. This program is a physical mathematical model able to predict the time dependent temperature, pore vapour pressure and humidity for concrete exposed to temperatures up to 800°C. This program uses thermodynamic steam tables and is based on the fundamental laws, namely Fick's law of diffusion, Darcy law and Fourrier law and also the mass and energy conservation equations. The effect of temperature on variations in permeability and also on the sorption isotherms is considered. Changes in porosity due to temperature and pressure are taken in account. Nevertheless, this model does not take into account the vapour that entrances in the specimen at the hot face. Input data for this problem are shown in Table 1.

Concrete	**HPC**
Saturation Water (Kg/m^3)	121
Water permeability (m/s)	0.98×10^{-14}
Age (days)	45
Humidity of concrete (%)	100
Humidity of environment (%)	100
Thickness of concrete (m)	1.3
Thermal conductivity (J/m.s.°C)	1.6
Heating rate	figure 1 (SA)
Pressure rate	figure 2 (SA)

Table 1: Input parameters to TEMPOR.2 (1D)

The computer calculations of temperature and pressure at 6,12,18 and 24 hours are illustrated in figures 4 and 5 respectively. These results helped in defining the positions of meters and sensors in the specimen. As shown in these figures after 24 hours, only 0.5 m of wall thickness is affected by temperature and by pressure applied.

CONCLUDING REMARKS

This paper gives the key information and defines the main components of a test equipment allowing study of the heat-mass transfers in concrete subjected to hygrothermal loading. In doing so, it has been necessary to develop some measurement methods and instruments such as a moisture meter to study these transitory regimes. Measures thus undertaken will provide useful inputs for the numerical simulation and for the validation of models.

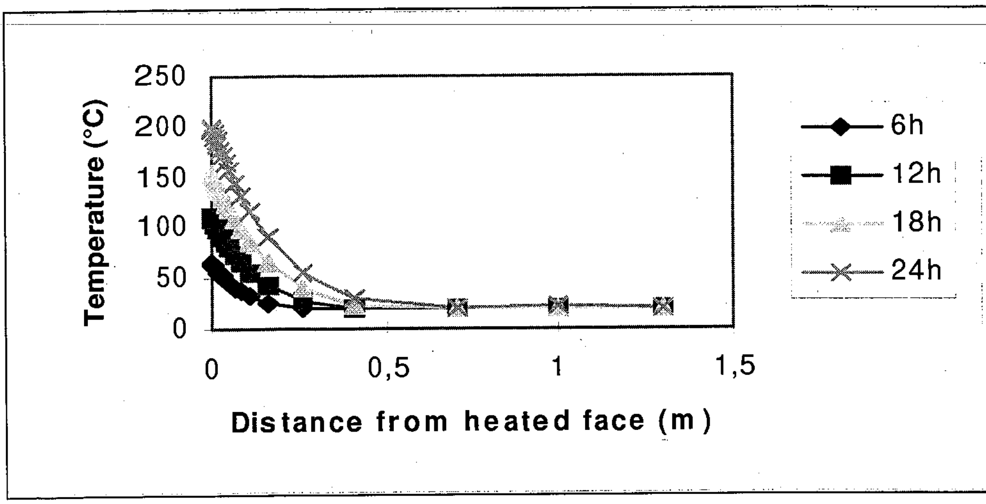

Figure 4: Temperature output

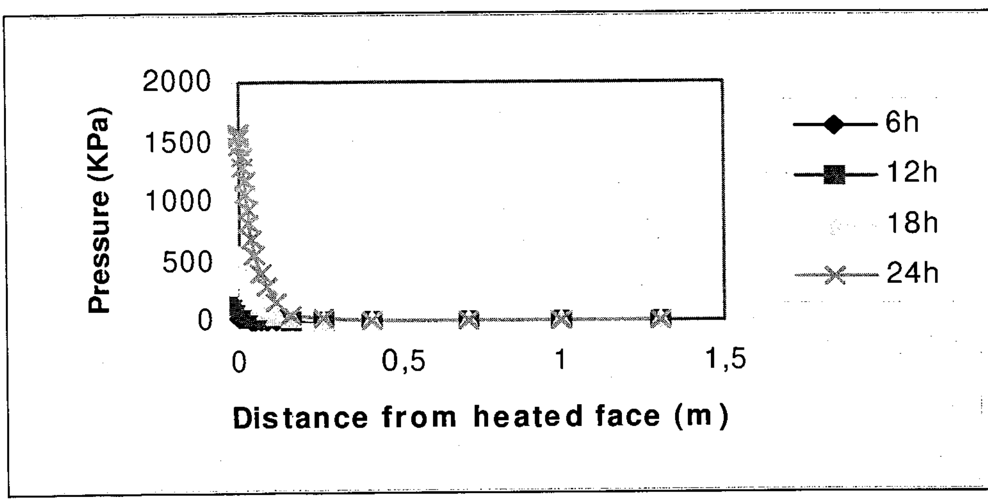

Figure 5: Pore pressure output

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