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Experimental investigation on transient thermo-mechanical behavior of cladding under LOCA using fuel simulator

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1. Introduction

The high-temperature deformation and rupture behavior of clad tube is essential to evaluate the coolant flow blockage and design of emergency core cooling system. The effect of the internal pressure, heating rate and temperature on ballooning deformation of Zircaloy-4 cladding has been widely investigated [1,2]. It has been observed that phase transformation from α to β phase plays an important role in the deformation of Zircaloy-4 [3,4]. The experiments performed with direct heating and IR heating techniques deviate from the in-reactor conditions and cannot be used for code validation. Hence an experimental facility has been designed for measurement of transient temperature and deformation over the clad tube by indirect heating using fuel simulator. The test results at 7.5 MPa internal pressure and 9.5 ^{o}C/sec heating rate are discussed in this paper.

2. Experimental setup and Results

The Fig. 1 shows the details of the test section. The clad tube (outer diameter of 9.5 mm) was placed concentrically inside a cylindrical enclosure (inner diameter of 50 mm). The clad tube of length 330 mm was mounted concentrically inside the cylindrical enclosure of length 450 mm. The clad tube was internally heated using a tungsten heater of 100 mm length. To measure transient temperature, eight K-type thermocouples (0.8 mm sheath diameter) were spot welded over clad tube using zirconium foil. To measure the transient deformation, four LVDTs are mounted to the wall of enclosure at central position. The Table 1 shows design characteristics of test section. The clad tube was pressurized using helium gas up-to the desired pressure through a SS pipeline connected to a cylinder (at 120 bar pressure). The pressure in the clad tube was measured by a pressure transducer mounted in the SS pipeline. To create non-oxidizing atmosphere around the clad tube, helium gas was supplied to the enclosure through the bottom end flange from a separate cylinder. The power was supplied to the tungsten heater through molybdenum rod and flexible copper cables (600 Amp capacity) connected to a programmable DC power supply (capacity 250 Amp and 25 Volts). For proper functioning of seal plugs, the molybdenum rod was used to maintain low temperature zone at both ends of the clad tube. The Fig. 2 shows test results at 7.5 MPa internal pressure and heating rate of 9.5 ^{o}C/sec. The transient was given after 21 seconds and at 73 seconds the temperature rise rate shown decrement which is indication of ballooning initiation. The LVDT 4 response has been observed at 73 seconds which confirms the initiation of ballooning in elastic region.

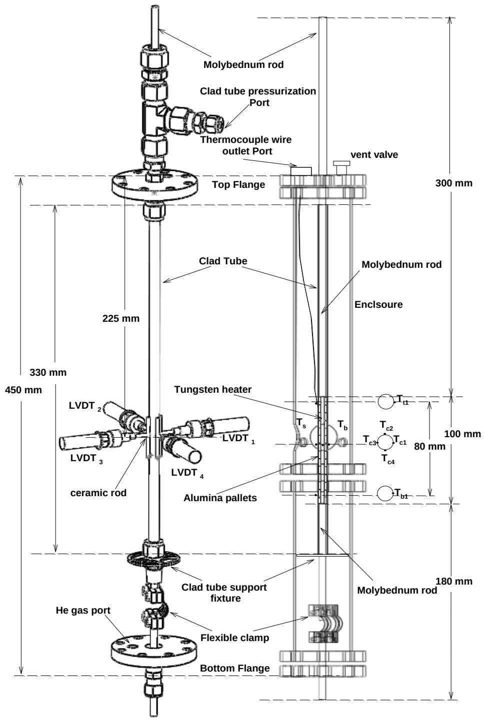

Figure 1: Details of Test section

Table 1: Design characteristics of test section

Component	Material	Dimensions
Clad tube	Zircaloy-4	Outer Dia. : 9.5 mm Inner Dia.: 8.36 mm Length : 330 mm
Heating element	Tungsten	Outer Dia. of Tungsten: 3 mm Length : 100 mm
	Moly-bednum	Outer Dia.of Moly. 6 mm Total Length : 300 mm
Pellets	Alumina (Al_2O_3)	Pellet of tungsten: O.D = 8.3 mm, I.D = 3.1 mm Length = 10 mm Pellet of Molybdenum: O.D = 8.3 mm, I.D = 6.1 mm Length = 50 mm
Enclosure	SS-316	Outer Dia.: 54 mm Inner Dia. : 50 mm Length : 450 mm
Clad tube annular support	SS-316	Outer Dia. : 49 mm Inner Dia. : 16 mm Thickness : 2 mm

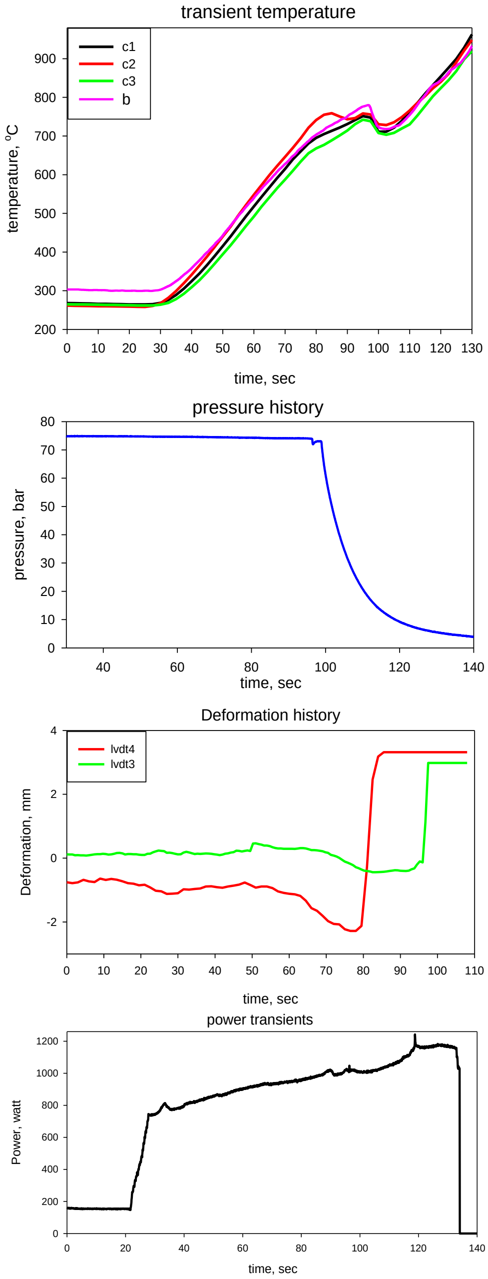

Figure 2: Transient temperature, pressure, deformation and power history

At 80 seconds the LVDT 4 shown a steep increment to 3.31 mm and corresponding decrement in temperature has been observed at location C3. At 97 seconds, the LVDT 3 shown a steep increment to 2.98 mm while pressure drop from 7.4 MPa to 7.2 MPa. This indicates the initiation of large plastic deformation in deformed zone. At 99 seconds the cladding burst has been observed which resulted into steep decrement of pressure and temperature.

The Fig. 3 shows distribution of injected power after transient. The major portion of input power is stored within the cladding and dissipates out slowly due to high thermal diffusivity of alumina pellets. Further the radiative heat transfer was major mode of heat dissipation from the surface of cladding.

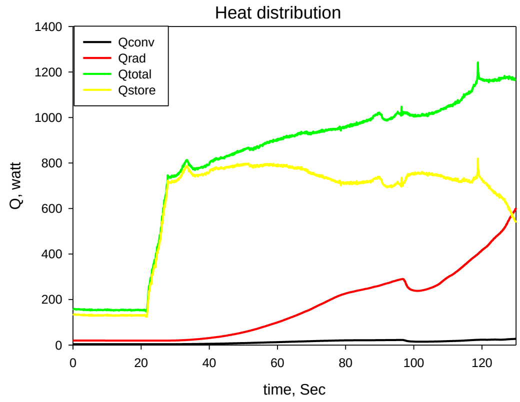

Figure 3: Heat distribution history

Convective heat transfer was calculated by Mc Adam Correlation (1954):

$$10^4 < Ra < 10^9$$

$$Nu = 0.59 Ra^{\frac{1}{4}}$$

$$q_{conv} = h_{avg}\left(T_{avg} - T_b\right)$$

Radiative heat loss from surface of cladding was calculated as:

$$Q_r = \frac{A_1 \sigma\left(T_{avg}^4 - T_s^4\right)}{\frac{1}{\varepsilon_1} + \left(\frac{1}{\varepsilon_2} - 1\right)\frac{A_1}{A_2}}$$

The Power loss in molybdenum was subtracted as:

$$Q_t = VI - IR_{mo}^2$$

The heat stored within the cladding was calculated as:

$$Q_{store} = Q_t - Q_r - Q_{conv}$$

3. Conclusions

The data from out of pile single rod experiment can provide vital information about transient temperature variation and deformation rate of the cladding, which can be extensively used for validation of Transient fuel response code like FRAPTRAN. Further, the results of present and subsequent tests will be used for development of burst criterion that will cover a wider range of temperatures.

4. Acknowledgement

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