

Effect of Groove Configuration on the Thermal and Pressure Responses of Embedded Optical Fiber Sensors in Heater Rods

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1. Introduction

In pressurized flow boiling experiments, critical heat flux (CHF) is typically identified by surface dryout followed by a rapid rise in wall temperature [1]. Accurate measurement of wall temperature along the heater rod is therefore essential for determining the onset and axial location of CHF. However, the limited spatial resolution of thermocouples makes it difficult to capture localized temperature increases between discrete measurement points. A distributed optical fiber sensor (OFS) provides continuous temperature measurements with high spatial resolution along the heated length of the rod [2].

Despite this capability, embedding the sensing fiber in an axial groove is a practical approach for integrating an OFS into a heater rod [3]. Because the OFS response is affected by both temperature and strain, deformation of the rod can influence the measured signal [4]. Under pressurized flow boiling conditions, external pressure can deform the rod, and the resulting strain can be transferred to the fiber through the groove. This issue is important because the groove geometry controls the mechanical constraint and strain transfer between the heater rod and the fiber. Thus, the influence of groove configuration must be quantified to distinguish the temperature response used for CHF detection from the contribution of pressure-induced strain [5].

In this study, finite element analysis (FEA) was conducted to evaluate the thermal and pressure responses of an embedded OFS in a heater rod model. The heated section consisted of an Inconel 600 tube and an alumina core, with the sensing fiber embedded in an axial groove formed on the outer surface of the alumina core. V-, T-, and R-shaped grooves were modeled at three sizes to assess groove effects. The nine models were analyzed under thermal, pressure, and combined thermal-pressure loads. The sensor response was quantified in terms of temperature sensitivity (S_T), pressure sensitivity (S_P), decoupling index (DI), and pressure contribution ratio (R_P). As a preliminary step toward CHF monitoring, separate static loading cases were used to quantify

temperature- and pressure-induced fiber strains. This approach establishes a mechanical baseline for assessing pressure-induced strain interference before investigating the localized transient thermal response relevant to CHF detection.

2. Methods

2.1. Heater Rods and Groove Configurations

Fig. 1 shows a three-dimensional schematic of the direct resistance heating rod designed to accommodate an embedded OFS. The heater rod consists of an Inconel 600 sheath, an alumina insulator placed inside the sheath, and copper electrodes assembled at both ends. The Inconel 600 sheath serves as the heating element during direct resistance heating. The alumina insulator provides electrical insulation between the heating element and the OFS embedded in the groove. To enable continuous temperature measurements along the heated section, an axial groove is formed on the outer surface of the alumina insulator. The OFS is embedded in this groove along the heater rod axis.

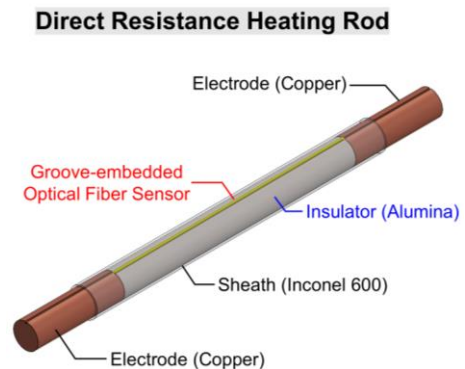


Fig. 1. Three-dimensional schematic of the direct resistance heating rod, showing the Inconel 600 sheath, alumina insulator with an axial groove for embedding the optical fiber sensor (OFS), and copper electrodes.

Fig. 2 presents the groove shapes and size levels used in the thermo-mechanical analysis. Fig. 2(a)–(c) show the V-, T-, and R-grooves, respectively. The OFS was embedded in the groove for each configuration. The groove geometry was defined using the top width (W_t), bottom width (W_b), and depth (h). Three size levels were defined by proportionally scaling W_t , W_b , and h while preserving the proportions of each groove shape. For size level 1, W_t and h were set to 0.5, and W_b was set to 0, 0.25, and 0.5 for the V-, T-, and R-grooves, respectively. For size level 2, W_t and h were set to 1.0, and W_b was set to 0, 0.5, and 1.0 for the same three groove types. For size level 3, W_t and h were increased to 1.5, and the corresponding W_b values were 0, 0.75, and 1.5 for the V-, T-, and R-grooves, respectively. Dimensions are summarized in Fig. 2(d). The combination of three groove shapes and three size levels resulted in a total of nine analysis models. This 3 × 3 model matrix enabled systematic comparison of the effects of groove shape and size.

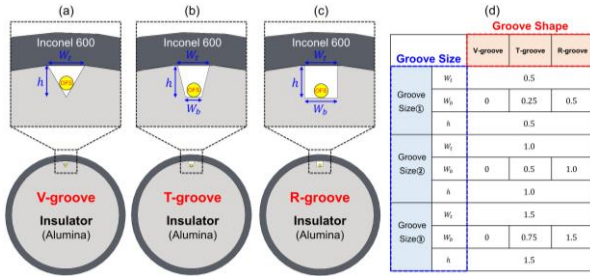


Fig. 2. Groove shape and size configurations on the alumina for embedding the OFS. (a) V-groove, (b) T-groove, and (c) R-groove designs, each defined at three size levels. (d) Summary of groove dimensions, including top width (W_t), bottom width (W_b), and depth (h) for each shape and size level.

2.2. Material Properties and Boundary Conditions

Fig. 3 shows the material configuration and properties used in the thermo-mechanical analysis. Fig. 3(a) presents the cross-sectional assembly of the Inconel 600 sheath, alumina insulator, and embedded OFS. The OFS was embedded in the groove formed on the outer surface of the alumina insulator. The OFS was modeled as a fused silica fiber surrounded by a polyimide coating. Fig. 3(b) summarizes the representative material properties assigned to the Inconel 600 sheath, alumina insulator, fused silica fiber, and polyimide coating. The listed properties include density, Young's modulus, Poisson's ratio, thermal conductivity, specific heat capacity, and the coefficient of thermal expansion (CTE). The constant material properties are reported as representative room-temperature values, whereas the CTE entries show temperature-dependent secant ranges referenced to 25 °C.

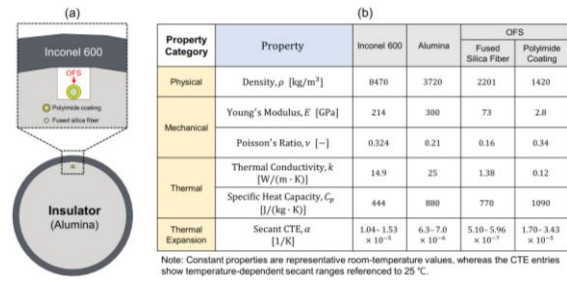


Fig. 3. Material configuration and representative properties for the heater rod model used in the thermo-mechanical analysis. (a) Assembly of the Inconel 600 sheath, alumina insulator, and OFS, including a fused silica fiber with a polyimide coating. (b) Representative properties of the constituent materials.

Fig. 4 presents the boundary conditions used in the thermo-mechanical analysis of the embedded OFS heater rod. Fig. 4(a) shows the mechanical constraints applied to the two end sections of the heater rod assembly. At $Z = 0$ mm, all translational and rotational degrees of freedom were constrained using a remote displacement. At $Z = 300$ mm, displacements in the X and Y directions and all rotational degrees of freedom were constrained, while displacement in the Z direction remained free. These constraints suppressed rigid-body motion while allowing axial deformation of the heater rod.

Fig. 4(b) shows the bonded contact conditions assigned between adjacent components. Bonded contact was assigned between the inner surface of the Inconel 600 sheath and the outer surface of the alumina insulator. The same condition was applied between the alumina groove surface and the outer surface of the OFS. The bonded interfaces were assumed to permit neither separation nor relative sliding, allowing deformation of the heater rod components to be transferred to the OFS. The same material properties, end constraints, and interface assumptions were applied to all nine models to isolate the effects of groove shape and size.

Fig. 4(c) shows the temperature and pressure loading conditions used to evaluate their separate and combined effects on the OFS response. In the thermal-only loading cases, uniform temperatures ranging from 25 to 400 °C were applied to the entire heater rod assembly while the external pressure was kept at atmospheric pressure (0 MPa gauge). For pressure-only loading, external pressure ranging from 0 to 25 MPa gauge was applied to the outer surface of the Inconel 600 sheath, while the temperature was maintained at the reference temperature of 25 °C. Under combined thermal-pressure loading, temperature and pressure were applied over the same ranges. The length-averaged axial strain along the embedded section of the OFS was evaluated under each loading condition. These responses provided the strain data used to calculate the performance metrics defined in Fig. 5.

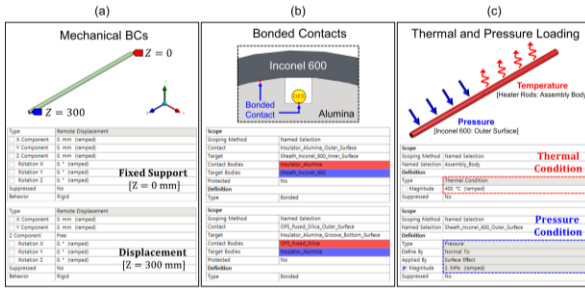


Fig. 4. Boundary conditions used in the thermo-mechanical analysis: (a) mechanical constraints at the rod ends, (b) bonded contact conditions between adjacent components, and (c) temperature and pressure loads applied separately and in combination to the entire assembly and the outer surface of the Inconel 600 sheath, respectively.

2.3. Performance Metrics for OFS Strain Response

Fig. 5 summarizes the definitions of the performance metrics used to quantify the OFS strain response. For each groove configuration, the axial strain of the OFS was extracted along the embedded fiber length. The extracted axial strain was averaged over the embedded fiber length to obtain the length-averaged axial strain ($\bar{\epsilon}_z$), representing the overall OFS response. The temperature sensitivity (S_T) was defined as the change in $\bar{\epsilon}_z$ per unit temperature change at atmospheric pressure (0 MPa gauge). The pressure sensitivity (S_P) was defined as the change in $\bar{\epsilon}_z$ per unit pressure change at the reference temperature of 25 °C. The decoupling index (DI) was used to quantify the relative dominance of the temperature response over the pressure-induced strain response. A higher DI indicates a greater dominance of temperature over pressure in the OFS response. The pressure contribution ratio (R_P) was used to quantify the relative contribution of pressure-induced strain to the total OFS response under combined loading. These metrics enabled comparison of the relative temperature- and pressure-induced strain contributions among the groove configurations.

$\bar{\epsilon}_z = f(T, P)$ $\bar{\epsilon}_z$: Length - averaged axial strain of OFS [$\mu\epsilon$]	
Temperature Sensitivity (S_T)	Pressure Sensitivity (S_P)
$S_T = \left. \frac{\partial \bar{\epsilon}_z}{\partial T} \right _{P=P_{ref}}$ [$\mu\epsilon/^\circ\text{C}$]	$S_P = \left. \frac{\partial \bar{\epsilon}_z}{\partial P} \right _{T=T_{ref}}$ [$\mu\epsilon/\text{MPa}$]
Decoupling Index (DI)	Pressure Contribution Ratio (R_P)
$DI = \frac{ S_T \Delta T_{ref}}{ S_P \Delta P_{ref}}$ [-]	$R_P = \frac{ \bar{\epsilon}_P }{ \bar{\epsilon}_T + \bar{\epsilon}_P }$ [-]
<ul style="list-style-type: none"> T: temperature [$^\circ\text{C}$] P: pressure [MPa] T_{ref}: reference temperature [25$^\circ\text{C}$] P_{ref}: reference pressure [0 MPa] 	<ul style="list-style-type: none"> ΔT_{ref}: reference temperature range [25$^\circ\text{C}$] ΔP_{ref}: reference pressure range [25 MPa] $\bar{\epsilon}_T$: temperature - only strain at $P = P_{ref}$ $\bar{\epsilon}_P$: pressure - induced strain relative to P_{ref}

Fig. 5. Performance metrics for the OFS strain response based on the length-averaged axial strain ($\bar{\epsilon}_z$): temperature sensitivity (S_T), pressure sensitivity (S_P), decoupling index (DI), and pressure contribution ratio (R_P).

3. Results

3.1. Temperature-Induced OFS Strain

Fig. 6 compares the temperature sensitivity (S_T) for the different groove shapes and sizes. The external pressure was fixed at atmospheric pressure (0 MPa gauge), while the temperature was varied from 25 to 400 °C. The S_T was calculated from the change in the length-averaged axial strain ($\bar{\epsilon}_z$) of the OFS per unit increase in temperature. For all groove shapes, S_T increased with groove size, ranging from 7.652–7.655 $\mu\epsilon/^\circ\text{C}$ for groove size 1 to 7.671–7.693 $\mu\epsilon/^\circ\text{C}$ for groove size 3. From groove size 1 to groove size 3, S_T increased by 0.24%, 0.36%, and 0.49% for the V-, T-, and R-grooves, respectively. At each size, the R-groove showed the highest S_T , followed by the T- and V-grooves. However, the differences associated with groove size and shape remained below 0.5% and 0.3%, respectively, indicating that groove geometry had only a limited effect on the S_T of the OFS.

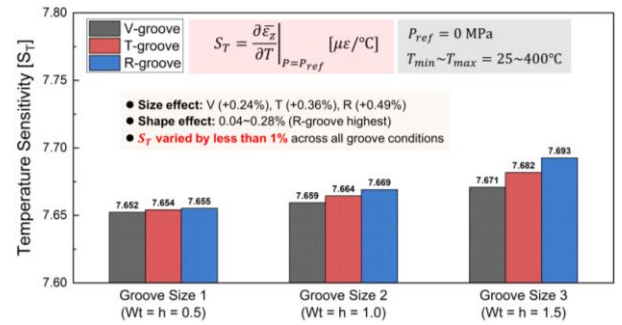


Fig. 6. Comparison of temperature sensitivity (S_T) by groove shape and size under temperature variations from 25 to 400 °C at atmospheric pressure (0 MPa gauge).

3.2. Pressure-Induced OFS Strain

Fig. 7 compares the pressure sensitivity (S_P) for the different groove shapes and sizes. The temperature was fixed at 25 °C, while the external pressure was varied from 0 to 25 MPa gauge. The S_P was calculated from the change in the length-averaged axial strain ($\bar{\epsilon}_z$) of the OFS per unit increase in external pressure. For all groove shapes, S_P increased with groove size, ranging from 1.646–1.652 $\mu\epsilon/\text{MPa}$ for groove size 1 to 1.674–1.710 $\mu\epsilon/\text{MPa}$ for groove size 3. From groove size 1 to groove size 3, S_P increased by 1.69%, 2.63%, and 3.52% for the V-, T-, and R-grooves, respectively. These increases were greater than the corresponding increases in S_T , indicating that groove enlargement had a greater effect on pressure-induced strain transfer than on temperature sensitivity. At each size, the V-groove showed the lowest S_P , whereas the R-groove showed the highest. The variation in S_P due to groove shape increased from approximately 0.35% for groove size 1 to 2.16% for groove size 3. Nevertheless, the variation across all groove shapes and sizes remained below 4%. These

results indicate that the V-groove reduced pressure-induced strain transfer relative to the T- and R-grooves, although the overall effect of groove geometry remained limited.

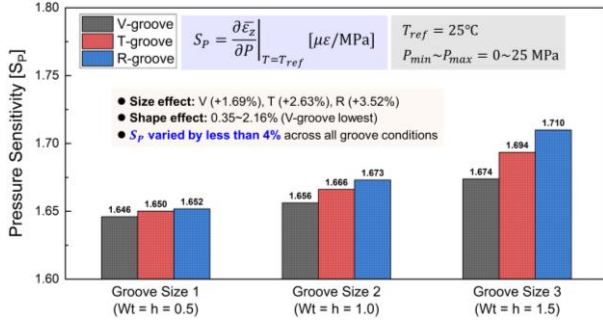


Fig. 7. Comparison of pressure sensitivity (S_P) based on the length-averaged axial strain of the embedded OFS for V-, T-, and R-grooves at three size levels under external pressures ranging from 0 to 25 MPa gauge at 25 °C.

3.3. Combined Temperature and Pressure Response

Fig. 8 compares the reference-based decoupling index (DI) for the different groove shapes and sizes. The DI was calculated using reference increments of $\Delta T_{ref} = 25$ °C and $\Delta P_{ref} = 25$ MPa. It represents the ratio of the temperature-induced OFS response to the pressure-induced OFS response under the selected reference increments. A higher DI indicates greater dominance of the temperature response over the pressure response. For all groove shapes, DI decreased with groove size, ranging from 4.634–4.649 for groove size 1 to 4.499–4.583 for groove size 3. From groove size 1 to groove size 3, DI decreased by 1.42%, 2.22%, and 2.91% for the V-, T-, and R-grooves, respectively. This reduction in DI was attributed to the greater increase in S_P than in S_T with increasing groove size. At each groove size, the V-groove exhibited the highest DI because it maintained a similar S_T while producing the lowest S_P , whereas the R-groove showed the lowest DI. Nevertheless, the variation in DI among the groove shapes remained below 2% at all size levels. Moreover, DI remained approximately 4.5 across all groove configurations, indicating that the temperature-induced response was approximately 4.5 times the pressure-induced response under the selected reference increments.

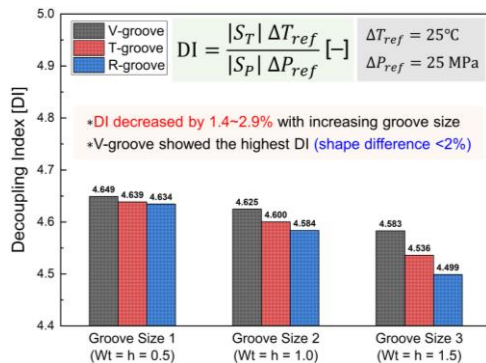


Fig. 8. Comparison of the reference-based decoupling index (DI) for different groove shapes and sizes using reference increments of $\Delta T_{ref} = 25$ °C and $\Delta P_{ref} = 25$ MPa.

Fig. 9 shows the pressure contribution ratio (R_P) as a function of temperature for groove size 2 ($Wt=h=1.0$) under an external pressure of 25 MPa gauge. The R_P represents the relative contribution of pressure-induced strain to the combined OFS response, with a lower value indicating less pressure influence. For all groove shapes, R_P decreased with increasing temperature, from 0.1809–0.1822 at 50 °C to 0.0304–0.0306 at 200 °C and 0.0140–0.0141 at 400 °C. Thus, R_P at 400 °C was approximately 92% lower than that at 50 °C. Because the external pressure was fixed, the pressure-induced strain contribution used to calculate R_P remained constant, whereas the temperature-induced strain increased with temperature. Consequently, the relative pressure contribution decreased, and the combined OFS response became increasingly dominated by temperature at elevated temperatures.

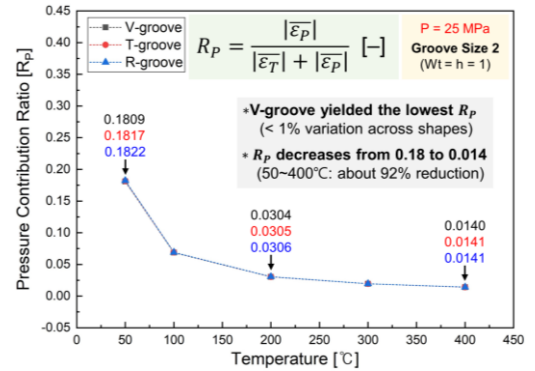


Fig. 9. Pressure contribution ratio (R_P) as a function of temperature for groove size 2 ($Wt=h=1.0$) under an external pressure of 25 MPa gauge.

At each temperature, the V-groove exhibited the lowest R_P , whereas the R-groove showed the highest value. However, the relative differences among the groove shapes remained below 1% throughout the investigated temperature range. These results indicate that groove shape had only a limited effect on R_P , although the V-groove consistently provided the smallest relative pressure contribution. The fully bonded interfaces excluded separation and relative sliding as sources of differences in strain transfer among the groove configurations. This assumption may explain the limited variation in length-averaged axial strain, although its contribution was not evaluated independently.

4. Conclusions

In this study, the temperature and pressure responses of an OFS embedded in a heater rod were examined through thermo-mechanical analysis. Temperature sensitivity varied by less than 1% among all groove configurations, indicating that groove geometry had little

effect on the thermal response. Pressure sensitivity increased with groove size, although the overall variation remained below 4%. The V-groove showed the lowest pressure sensitivity and the highest decoupling index, indicating reduced pressure-induced strain transfer while preserving temperature sensitivity. However, the differences in the decoupling index among the groove shapes remained below 2% at all size levels. Under combined loading for groove size 2 at 25 MPa gauge, the pressure contribution ratio decreased by approximately 92% as the temperature increased from 50 to 400 °C. The differences in the pressure contribution ratio among the groove shapes also remained below 1% throughout the investigated temperature range. Therefore, temperature increasingly dominated the OFS response at elevated temperatures, regardless of groove shape. Taken together, the evaluated groove configurations exhibited similar strain responses, with the strain induced by temperature exceeding that induced by pressure under the selected reference increments. The limited variation among configurations supports considering machinability, fiber installation, and structural requirements alongside the evaluated strain metrics when selecting a groove within the evaluated range. Further transient thermal analysis and experimental validation, including assessment of heat transfer from the rod surface to the fiber and calibration of the optical response to temperature and strain, are needed to evaluate early CHF detection performance.

5. Acknowledgement

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