ELASTIC FUEL ROD DEFLECTIONS AND SPACER REACTORS DUE TO TRANSVERSE TEMPERATURE GRADIENTS

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SUMMARY

Transverse temperature gradients can occur in fuel rods due to power tilts or to thermal-hydraulic variations in the coolant subchannels which surround the fuel rod. Evaluations of the fuel rod deformations and spacer reaction forces associated with thermal gradients occurring during long term power operation involve complex computer analyses which include creep relaxation effects. During certain transient or accident situations even more severe short term thermal gradients can be developed due to subchannel power-to-flow imbalances wherein the associated elastic fuel rod deformations and spacer reaction forces are of interest both from a structural and a thermal-hydraulic feedback point of view.

This paper evaluates the elastic fuel rod lateral deflections and the spacer reaction forces for a fuel rod subjected to a uniform lateral temperature gradient along its entire length. Dimensionless displacement and force functions were evaluated using simple beam formulas and superposition principals and are presented for from two to seven equal pitched spacers (or conversely, for one to six spans). The largest deflection occurs in the span nearest the free ends and the largest reaction force occurs at the first spacer in from the end. The bending moment at the center of the six-span case due to the reaction forces is about 90% of the imposed thermal bending moment ($EI\alpha G$) so the six-span results should be fairly representative for the infinite span case. For the six-span case the maximum lateral deflection (in the end span) $\delta_{\max}$, the maximum rotation (at the end spacer) $\Theta_{\max}$, and the maximum spacer force (at the first spacer in from the end) $F_{\max}$ are as follows:

$$\delta_{\max} = 0.05 \cdot \alpha G L^2 , \quad \theta_{\max} = 0.24 \cdot \alpha G L , \quad F_{\max} = 1.6 \cdot EI\alpha G/L$$

These results should be useful to core designers to gain insight into thermal gradient induced distortion effects during accident conditions although more complex analyses which more accurately account for the axial variation in thermal gradients and other non-linear effects should be made for confirmation.

1. Introduction

Fuel rods in operating reactors are often subjected to thermal gradients due to radial power tilts or thermal-hydraulic variations in the coolant subchannels which surround the fuel rod. The fuel rods typically have lateral restraints in the form of grid spacers or wire wraps located at intermittent positions along the fuel rod length. The spacer reaction forces and the lateral deflections between spacers are of interest from the mechanical and thermal hydraulic points of view. To accurately evaluate these forces and deflections during long-term operation, complex computer analyses are usually required. These analyses take into account axial variations of temperature level and temperature gradient, creep relaxation effects [1], clearances within the spacers, and axial friction forces which may develop at spacer locations. During short-term transient or accident situations, the thermal gradients can substantially increase owing to coolant subchannel power-to-flow imbalances, wherein the associated elastic fuel rod deformations and spacer reaction forces are of interest.

This paper presents the results of an elastic analysis of an idealized case which assumed that a fuel rod with uniformly pitched spacers is subjected to a constant transverse temperature gradient along its entire length. The resulting deflections and spacer reaction forces are presented in the form of dimensionless parameters for cases ranging from one to six spans as well as for the semi-infinite case. These results should be useful to core designers making scoping calculations, although the more complex and detailed analyses which consider the effects mentioned above should be made for confirmation.

The analytical method employed uses straight forward beam formulas and compatability and superposition principals. Only lateral forces are considered at the spacer locations, and no friction effects or bending moments are included. The dimensionless spacer reaction forces and deflection curves are presented in Section 2, and a simple example illustrating the application of the dimensionless data is presented in Section 3.

2. Results

The results of analyses of finite-length fuel rods with two to seven equally pitched spacers and of a semi-infinite fuel rod with equally pitched spacers are given in Fig. 1 in the form of dimensionless force (F*) and deflection (y*) parameters. The actual force (F) and deflection (y) values are obtained as

$$F = F^* \cdot EI\alpha G/L,$$

$$y = y^* \cdot \alpha L^2 G,$$

where

α = instantaneous coefficient of thermal expansion,

G = imposed thermal gradient,

L = distance between spacers,

EI = fuel rod bending stiffness.

Any consistent system of units can be used for the above input data.

The results shown in Fig. 1 for the uniform temperature gradient cases studied indicate that the largest fuel rod deflection occurs in the span nearest the free end(s), and the deflection in spans removed from the end approaches zero after about three spans. The largest spacer reaction force occurs in the first spacer from the end, and the reaction forces rapidly diminish at spacer locations further removed from the end. For the semi-infinite case, the maximum lateral deflection (y_{max}), the maximum rotation at a spacer location (Θ_{max}), and the maximum spacer reaction force (F_{max}) are as follows:

$$y_{max} = 0.05 \cdot \alpha L^2 G,$$

$$\Theta_{max} = 0.24 \cdot \alpha L G,$$

$$F_{max} = 1.6 \cdot EI\alpha G/L.$$

The thermal stresses developed in the fuel rod are simply those due to the applied spacer reaction forces since the unrestrained thermal stress is zero. A very interesting feature which illustrates that only end effects are important in this class of problem becomes apparent, as shown in the bending moment diagram for the semi-infinite case (Fig. 2). This figure indicates that the net moment due to the spacer reaction forces is very nearly equal (but opposite in sign) to the imposed thermal moment (EIαG) after about three spans from the end. This essentially means that for a very long fuel rod with many spacers, only the spacers near the end are required to keep the rod straight when it is subjected to a uniform temperature gradient. The same conclusion cannot be made for the nonuniform temperature gradient case.

3. Application

Consider a 60-in. long fuel rod with spacers located every 10 in. subjected to a thermal gradient of 100°F/in. and the following material and section properties:

$$\alpha = 10 \times 10^{-6}\ {}^\circ F^{-1},$$

$$E = 20 \times 10^{6}\ \text{psi},$$

$$OD = 0.3\ \text{in.},$$

$$ID = 0.27\ \text{in.},$$

$$I = \frac{\pi}{64} \times (0.3^4 - 0.27^4) = 1.37 \times 10^{-4}\ \text{in.}^4.$$

Determine the maximum deflection, spacer force, and stress level. From the six-span case shown in Fig. 1, the maximum F* and y* values are 1.615 and 0.05, respectively. Therefore, the maximum deflection is

$$y_{max} = y^*_{max} \cdot \alpha L^2 G = 0.05 \times 10^{-5} \times 10^2 \times 10^2 = 0.005\ \text{in.},$$

occurring about 4 in. from the end. The maximum spacer force is

$$F_{max} = F^*_{max} \cdot EI\alpha G/L = 1.615 \times 20 \times 10^6 \times 1.37 \times 10^{-4} \times 10 \times 10^{-6} \times 10^2/10 = 0.44\ \text{lb},$$

occurring at the first spacer from the end. The maximum bending moment is 1.269 x EIαG, occurring at the first spacer from the end, and the maximum bending stress is

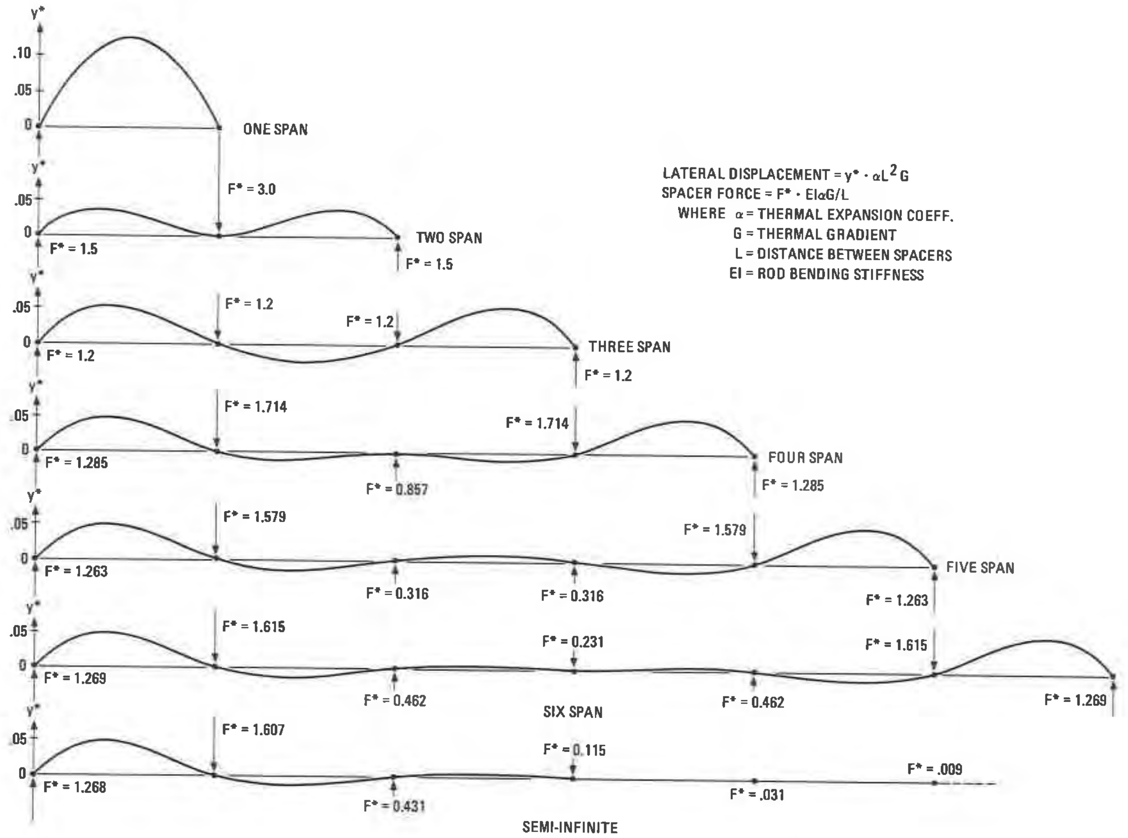
$$\sigma_{max} = \frac{Mr_o}{I} = 1.269 \times E\alpha G \times r_o = 1.269 \times 20 \times 10^6 \times 10 \times 10^{-6} \times 10^2 \times 0.15 = 3{,}800 \text{ psi.}$$

4. Conclusions

The results for the elastic deflections and spacer reaction forces developed in a fuel rod with equally pitched spacers subjected to a uniform temperature gradient are useful for scoping analyses. Nonlinear effects associated with nonuniform temperature gradients, creep, clearance, and friction effects at the spacers, and temperature-varying material properties should be evaluated with more sophisticated computer analyses.

Reference

[1] SUTHERLAND, W. H., ATWOOD, V. B., "CRASIB, Creep Analysis of Statically Intermediate Beams, Computer Program," March 23, 1970, preliminary CRASIB Workshop Issue.



LATERAL DISPLACEMENT = $y^* \cdot \alpha L^2 G$
SPACER FORCE = $F^* \cdot EI\alpha G/L$
WHERE α = THERMAL EXPANSION COEFF.
G = THERMAL GRADIENT
L = DISTANCE BETWEEN SPACERS
EI = ROD BENDING STIFFNESS

Fig. 1

LATERAL DISPLACEMENTS AND SPACER REACTION FORCES FOR FUEL RODS SUBJECTED TO A UNIFORM LATERAL THERMAL GRADIENT

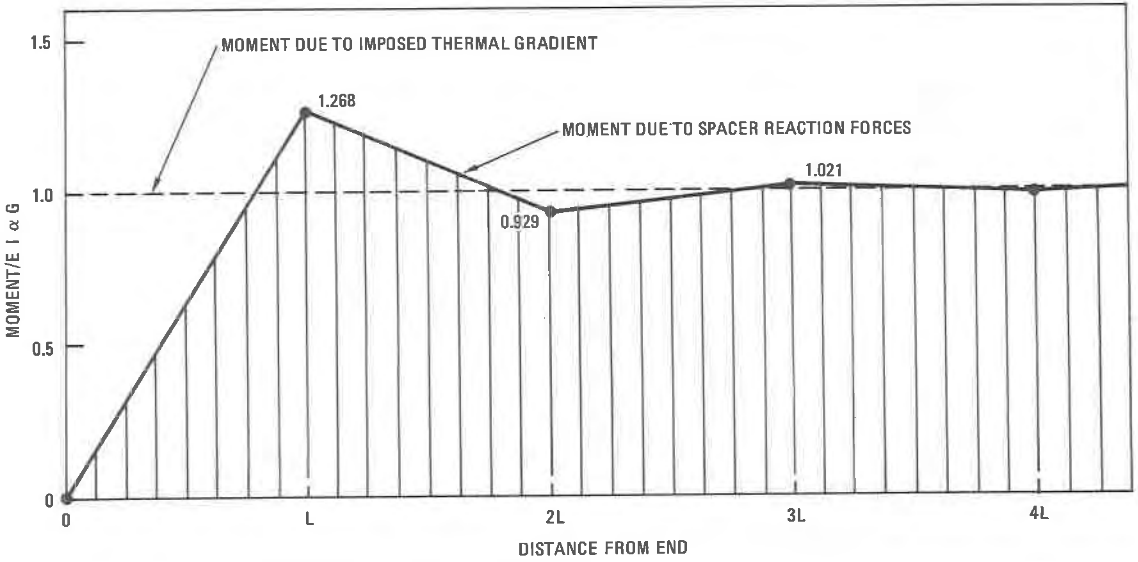


FIG. 2

FUEL ROD BENDING MOMENT DIAGRAM FOR SEMI-INFINITE CASE