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A SIMPLIFIED HEAT TRANSFER ANALYSIS OF THE
BULK SHIELDING REACTOR IN THE THERMALLY
INDUCED TURBULENT FLOW REGIME

SUMMARY

The present work was performed at the request of the Bulk Shielding Facility. The analysis is based upon two areas of information: First, experimental fluid temperature rise data for the B.S.R. at power levels up to one megawatt and, second, knowledge of the friction factor and heat transfer rate in the thermal turbulence regime where a superposed free and forced convection type of flow exists.

As a result of this analysis the following two conclusions may be made:

- (1) Above 100 Kw in the B.S.R. the hot exhaust jet above the reactor contributes $5/6$ of the total buoyant force causing flow through the reactor while the reactor section itself contributes only $1/6$. This is equivalent to a water chimney about 3.5 feet high.
- (2) A conservative estimate of the onset of local boiling in the B.S.R. (for the 22A loading and 12°C water) is 1700 Kw. No prediction was made for the onset of film boiling.

NOMENCLATURE
(except that defined in Sections I and II)

Symbol	Quantity	Unit
c_p	Specific heat of water	B/lb. F.
d_h	Hydraulic diameter of flow channel	ft.
g	Gravitational acceleration	ft/hr. ²
k	Thermal conductivity of water	B/hr ft ² F.
L	Fuel plate length	ft.
Nu	Nusselt modulus; $Nu = \frac{q(Z) d_h}{k [t_w(Z) - t_f(Z)]}$	none
$q(Z)$	Heat transfer rate per unit area of fuel plate at level, Z.	B/hr ft ²
	$q(m) = \int_0^1 q(Z) dZ$	
	$q(1/2)$ is maximum $q(Z)$ occurring center of reactor	
	$q(1)$ is minimum $q(Z)$ occurring top of reactor	
Re	Reynolds modulus; $Re = \frac{V d_h}{\nu}$	(none)
S	Channel width between plates	(ft)
$t(Z)$	Temperature at level Z	°F.
	$t_f(Z)$ - fluid mixed mean temperature	
	$t_w(Z)$ - wall (fuel plate) temperature	
V	Mean fluid velocity	ft/hr.
Z	Normalized vertical coordinate having the values 0, 1/2, and 1 at the bottom, middle and top of the reactor.	ft.

Symbol	Quantity	Unit
β	Temperature coefficient of volume expansion of water	($^{\circ}\text{F}^{-1}$)
$\theta(Z)$	Temperature excess above pool temperature $\theta(Z) = t(Z) - t_f(0)$ The subscripts f or w on θ have the same meaning as defined in t above.	$^{\circ}\text{F}$
λ	Friction factor (for isothermal laminar flow in long pipes of circular cross section $\lambda = 64/\text{Re}$)	(none)
μ	Dynamic viscosity of water	lb/ft hr
ν	Kinematic viscosity of water	ft ² /hr

I. Data on which analysis is based and source of data.

(A) from Bohanan (Reference 1)

- (1) Number of fuel plates per element - 18
- (2) Plate width, $W = 2.574$ inches
- (3) Plate length, $L = 2$ ft.
- (4) Channel width (between plates) $S = 0.117$ inches
- (5) Vertical distribution of heat flux in fuel plate is sinusoidal with:

$$\frac{q(1/2)}{q(m)} = 1.227 \quad (\text{maximum flux-occurring at center of reactor})$$

$$\frac{q(1)}{q(m)} = 0.568 \quad (\text{minimum flux-occurring at top of reactor})$$

(B) from Maienshein (Reference 2)

- (1) Vertical distance from center of reactor to pool surface is 17.5 feet.

(C) from ORNL-1682 (Reference 3)

- (1) Pool temperature, $t_f(0) = 12^\circ\text{C}$
- (2) From Table A-1 the percent of the total power that is generated in elements 15, 16, and 25 is 4.41, 3.89, and 5.18, respectively.
- (3) The following is an excerpt from Table 8

Reactor Power Kw.	$\theta_f(1) - ^\circ\text{C}$	
	(Element 15)	(Element 16)
100	12	11
200	15.7	15
500	29.5	29
1000	36.5	37

II. Basic system parameters computed based on data in I above.

- (1) Hydraulic diameter; $d_h = \frac{2 S W}{W + S} = 0.01864$ feet.
- (2) Heat transfer area per channel; $A_h = 2WL = 0.858$ feet²
- (3) Flow area per channel; $A_f = WS = 0.00209$ feet²
- (4) $\frac{d_h}{2S} = 0.956$
- (5) Pool temperature $t_f(0) \approx 54^\circ\text{F}$
Boiling temperature at pressure of center of reactor is 234°F .
- (6) From average line through Table 8 data above get

$$\theta_f(1) = 0.432 [q(m)]^{0.56} \dots\dots\dots (1)$$

for $1000 < q(m) < 10,000$ B/hr. ft² and $\theta_f(1)$ in $^\circ\text{F}$

III. Basic equations for velocity and fluid temperature rise calculations.

The heat equation is:

$$q(m) = \left(\frac{S}{2d_h L} \right) \mu c_p \theta_f(1) \text{ Re} \dots\dots\dots (2)$$

$$\text{or } q(m) = 0.1308 (\mu c_p) \theta_f(1) \text{ Re} \dots\dots\dots (2a)$$

The dynamic equation is:

$$F \text{ Re}^2 = \left(\frac{\beta}{\nu^2} \right) g d_h^3 \theta_f(1) \dots\dots\dots (3)$$

where

$$F = \frac{\lambda}{1 + \frac{B_j}{B_r}} \dots\dots\dots (4)$$

and $\frac{B_j}{B_r}$ is the ratio of the buoyant force due to the hot jet exhausting from the reactor to the buoyant force due to the reactor section alone.

Eliminating Re from (2a) and (3) get:

$$\theta_f(1) = \left(\frac{7.65 q(m)}{\rho c_p} \right)^{2/3} \left(\frac{F}{\beta g} \right)^{1/3} \frac{1}{d_h} \dots\dots\dots (5)$$

IV. An Interpretation of the $\theta_f(1)$ Experimental Data.

From B.S.R. experimental results (Equation 1) and Equations (2a) and (3) get:

$$F = \frac{0.275}{Re^{0.165}} \quad \text{for } 200 < Re < 1000 \dots\dots\dots (6)$$

From experience with thermal turbulence in References 4 and 5 one would expect the friction factor, λ , to be at least 6 times greater than F in Equation (6). Thus, from Equation (4), get:

$$\frac{B_j}{B_r} = 5 \dots\dots\dots (7)$$

Evidently 5/6 of the buoyant force causing flow through the reactor is due to the jet above the reactor and only 1/6 is due to the reactor section itself. This is equivalent to an artificial chimney about 3.5 feet long.

V. Estimation of Onset of Local Boiling.

Local boiling can only occur after the wall temperature reaches 234°F which corresponds to a value of $\theta_w(Z) = 180^\circ\text{F}$. The wall temperature will be computed at two positions, the middle and top of the reactor. ~~Let Δt_f be the temperature level of the wall or plate above the mixed mean fluid temperature at that height.~~ The mixed mean fluid temperature rise through the reactor, $\theta_f(1)$, is known from Equation (1) to a heat flux of $10,000 \text{ B/hr ft}^2$; this curve will be extrapolated to $20,000 \text{ B/hr ft}^2$ for the present analysis. So the temperature level of the wall above the pool temperature, $\theta_w(Z)$, is given by:

$$\begin{aligned} \theta_w(1) &= \theta_f(1) + [t_w(1) - t_f(1)] \quad \text{at top of reactor} \\ \theta_w(1/2) &= \frac{\theta_f(1)}{2} + [t_w(1/2) - t_f(1/2)] \quad \text{at middle of reactor} \end{aligned} \dots\dots\dots (8)$$

The Nusselt modulus, Nu, is, by definition:

$$t_w(1) - t_f(1) = \frac{0.568 q(m) d_h}{k(1) Nu} \dots\dots\dots (9)$$

$$t_w(1/2) - t_f(1/2) = \frac{1.227 q(m) d_h}{k(1/2) Nu}$$

A conservative estimate of the lowest value one might expect for Nu is 10. From this one calculates:

q(B/hr ft ²)	$\theta_f(1)$	$[t_w(1) - t_f(1)]$	$[t_w(1/2) - t_f(1/2)]$	$\theta_w(1)$	$\theta_w(1/2)$
5,725	54.5	16.5	37	71	64
11,450	81	32	72.5	113	113
17,170	101	47	107.5	148	158

The higher temperature occurs at the middle of the reactor for higher values of q, according to these calculations. This is not necessarily true because Nu is probably greater in the middle; however, this leads to a conservative result. Extrapolation of the above $\theta_w(1/2)$ data to the permitted value of 180F gives a q equal to 20,000. Based on the q to element 25 this corresponds to a B.S.R. power of 1,700 Kw. I believe this to be a conservative estimate of the power at which local boiling will occur.

D. C. Hamilton

DCH:tkc

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