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PUBLICAÇÃO IPEN 52 IPEN - Pub - 52	OUTUBRO/1982

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SÃO PAULO – BRASIL

Série PUBLICAÇÃO IPEN

INIS Categories and Descriptors

E11

HEAT EXCHANGERS
HEAT TRANSFER
MATHEMATICAL MODELS
THERMAL CYLING
THERMAL SHOCK
TRANSIENTS

CEN

Received in July 1982.
Aproved for publication in August 1982.
Writing, orthography, concepts and final revision are of exclusive responsibility of the Authors.

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ABSTRACT

A mathematical model has been developed to analyze the transient thermal response of the I.P.E.N. water loop during change of power operations. The model is capable of estimating the necess.ry test section power and heat exchanger mass flow rate for a given operating temperature. It can also determine the maximum heating or cooling rate to avoid thermal shocks in pipes and components.(author)

1 – INTRODUCTION

C.E.A. (Circuito Experimental de Água) is a water loop designed to study thermal hydraulic problems of interest in nuclear reactor technology. A detailed description of C.E.A. will be published in a forthcoming report[1]. Figure 1 shows a simplified diagram of the loop.

As shown in Figure 1, the main components of the loop are: an energy source of electrically heated tubes in the test section, several heat exchangers and a centrifugal pump.

The single-stage centrifugal canned pump has a performance curve hat can be approximated by the following correlation:

$$H^* = 332.3 + 0.23216\,Q - 0.00108\,Q^2$$

where H is the pump head in ft and Q the volumetric flow rate is gpm.

The main shell – and – tub heat exchanger (C – 101) has 25 U tubes – 3/4", triangular pitch, and the cooling water at the inlet can be split into four different chambers so that a different number of tubes can be used according to the thermal load. The total tube area is 30.8 ft^2.

In normal operation, the loop is actuated from the control board. Care should be taken in order not to use too high a rate of water temperature change. In reactor components, for instance, the norms recommend rates under $100^\circ F/h$.

The aim of this study is to find the dynamic characteristics of C.E.A. during power changes. This would provide a rough estimate on how to act on the control board in order to reach a given operation condition and the necessary time interval to achieve it.

The dynamic response of the C.E.A. during operational transients basically depends on the time response of the heat exchanger to a given power change in the test section. In short, this study tries to determine the time constant of the heat exchanger.

2 – PHYSICAL MODELS

In order to study the dynamic thermal response of the C.E.A. one needs to apply a balance of energy (First Law of Thermodynamics) to the entire loop. Assuming the loop is thermally insulated,

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* Please see Nomenclature, page 15.

$$\begin{bmatrix} \text{Rate of accumulation} \\ \text{of energy} \end{bmatrix} = \begin{bmatrix} \text{Heat added} \\ \text{to test section} \end{bmatrix} - \begin{bmatrix} \text{Heat removed} \\ \text{in the heat exchanger} \end{bmatrix}$$

Symbolically,

$$Mc_{ps} \frac{dT}{d\theta} = \dot{Q}_A - \dot{Q}_R \tag{1}$$

Where Mc_{ps} is the heat capacity of the loop and T is the average loop temperature, θ represents the variable time.

A heat balance (see Fig. 2) on the heat exchanger gives,

$$\dot{Q}_R = W_t c_{pt} (t_2 - t_1) = W_s c_{ps} (T_1 - T_2) \tag{2}$$

Q_R can also be expressed in terms of the logarithmic mean overall temperature difference, (LMTD)[2]

$$\dot{Q}_R = UAF_t \cdot (LMTD) \tag{3}$$

where,

$$LMTD = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left(\dfrac{T_1 - t_2}{T_2 - t_1}\right)} \tag{4}$$

or

$$LMTD = \frac{(T_1 - T_2) - (t_2 - t_1)}{\ln\left(\dfrac{T_1 - t_2}{T_2 - t_1}\right)} \tag{5}$$

Using (2), it comes

$$LMTD = \frac{\dot{Q}_R/W_s c_{ps} - \dot{Q}_R/W_t c_{pt}}{\ln[(T_1 - t_2)/(T_2 - t_1)]} \tag{6}$$

Using (3), Q_R can be eliminated resulting,

$$\ln\left(\frac{T_1 - t_2}{T_2 - t_1}\right) = UAF_t \left[\frac{1}{W_s c_{ps}} - \frac{1}{W_t c_{pt}}\right]$$

or

$$\frac{T_1 - t_2}{T_2 - t_1} = \exp\left\{U A F_t \left[\frac{1}{W_s c_{ps}} - \frac{1}{W_t c_{pt}}\right]\right\} \equiv E \qquad (7)$$

Using (2) and defining $\Delta T = T_1 - t_1$ it comes

$$\dot{Q}_R = \frac{\Delta T\,(E - 1)}{E/(W_s c_{ps}) - 1/(W_t c_{pt})} \qquad (8)$$

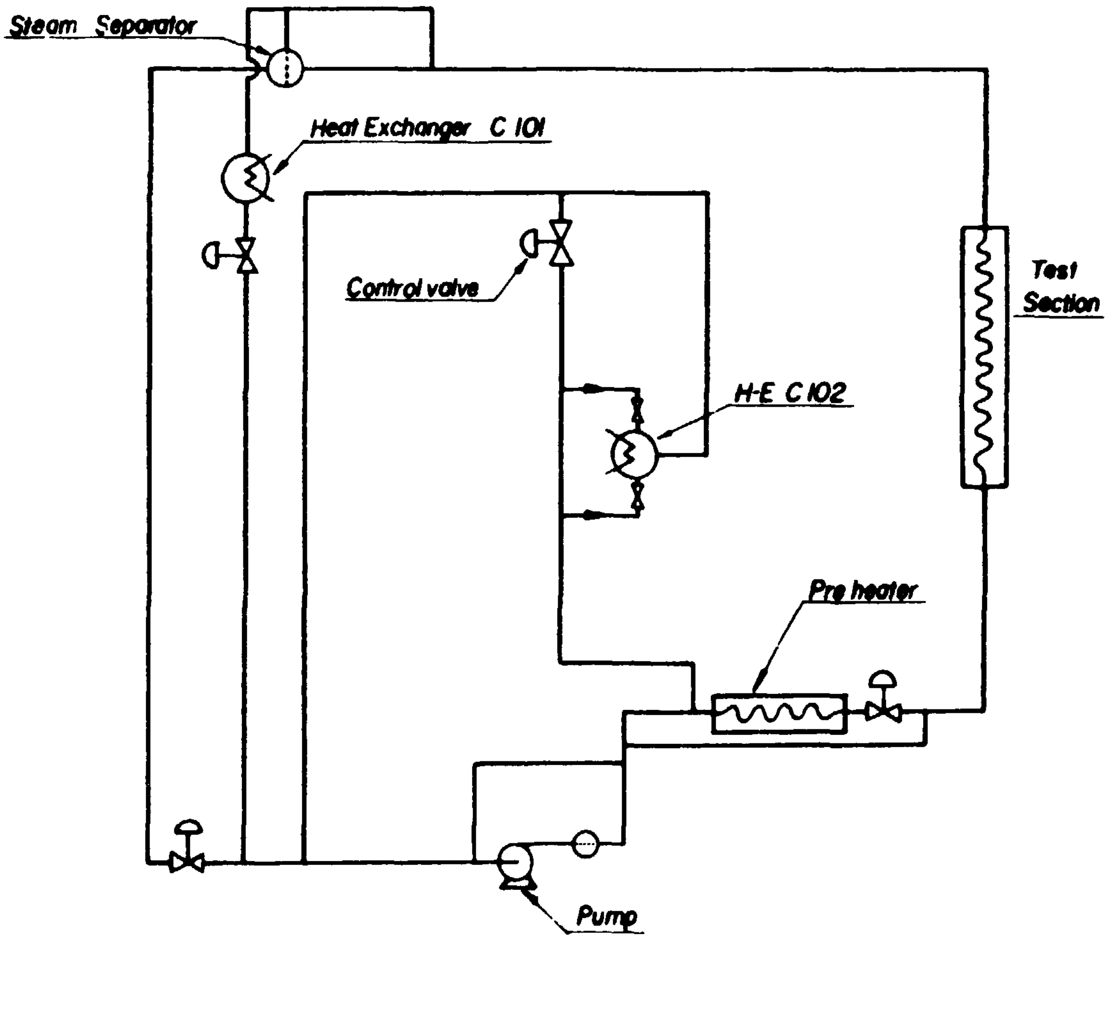

Figure 1 – Simplified diagram of the loop.

3 – METHOD OF SOLUTION

A first order approximation is used to find the temporal variation of the fluid average temperature. Therefore at time step n + 1 the average loop temperature is given by

$$T^{n+1} = T^{n} + \frac{dT}{d\theta}\,\Delta\theta \tag{9}$$

Where $dT/d\theta$ is evaluated from (1). It is assumed here that at any point in the loop the time derivative $dT/d\theta$ is the same (see Fig. 3). This is a reasonable assumption since time delays between components are in the order of seconds whereas in operational transients one thinks in terms of minutes. Therefore, using (9), the temperature at the inlet of the heat exchanger can be expressed as

$$T_1^{n+1} = T_{IN}^{n} + \frac{\dot{Q}_A^{n+1}}{W_{ts}c_{ps}} + \frac{dT}{d\theta}\,\Delta\theta$$

or

$$T_1^{n+1} = T_{IN}^{n} + \frac{\dot{Q}_A^{n+1}}{W_{ts}c_{ps}} + \frac{1}{Mc_{ps}}\left[\dot{Q}_A^{n+1} - \dot{Q}_R^{n+1}\right]\Delta\theta \tag{10}$$

In equation (10) T_{IN}^{n} and $\dot{Q}_A^{n+1}$ are known functions of time. The evaluation of $\dot{Q}_H^{n+1}$ from equation (8) involves an iterative process which is the same method used in steady-state design of heat exchangers.

Iterative Scheme

Here the superscript refers to the iteration. The superscript in referring to variable time is dropped for simplicity.

(1st) Assume $T_c^1 = T_1$

$t_c^1 = t_1$

$F_t^1 = 1$

Compute U^1

$\dot{Q}_R^1$

T_2^1

t_2^1

(2nd) Use $T_c^i = T_c^{i-1}$; $i = 2, n$

$$t_c^i = t_c^{i-1}$$

Compute F_t^i

Compute U^i, Q_R^i, T_2^i, t_2^i

(3^{nd}) Compute T_c^{i+1}

t_c^{i+1}

F_t^{i+1}

Compute $\dot{Q}_R^{i+1}$, U^{i+1}, T_2^{i+1}, t_2^{i+1}

(4^{th}) Compare T_2^{i+1} with T_2^i and check the convergence criteria. If not satisfied go to the 2^{nd} step of the iteration. If satisfied make a check on the value of $\dot{Q}_R$ using the energy balance given equation (2) (quasi – steady analysis). Compute the temperature gradiente from equation (1). Finally, evaluate T_1^{n+1} from equation (10) and proceed to the next time step starting a new iterative process (1^{st} step).

Correlations[2]

(1) Heat transfer coefficient in the tube side, h_i

$$\frac{h_i D_i}{k} = 0.027\ (Re_t)^{0.8}\ (Pr_t)^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

with k,μ and Pr calculated at the caloric temperature, T_c

(2) Heat transfer coefficient in the shell side, h_s

$$\frac{h_s D_{es}}{k} = 0.36\ (Re_s)^{0.55}\ (Pr_s)^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

with k, μ and Pr calculated at the caloric temperature, t_c. D_{es} is the shell side equivalent diameter.

(3) Overall heat transfer coefficient, U

$$\frac{1}{U} = \frac{1}{h_{io}} + \frac{1}{h_s}$$

Where $h_{io} = h_i\ D_i/D_o$; D_i and D_o are respectively the internal and external tube diameter.

(4) Caloric temperature, T_c and t_c.

$$T_c = T_2 + F_c\ (T_1 - T_2)$$

$$t_c = t_1 + F_c\ (t_2 - t_1)$$

where,

$$F_c = 0.4887 \left(\frac{T_2 - t_1}{T_1 - t_2} \right)^{1.784}$$

(5) Wall temperature, T_w

$$T_w = T_c + \frac{h_{io}}{h_s + h_{io}} (T_c - t_c)$$

(6) Fractional ratio of the true temperature difference to the LMTD, F_t.

$$F_t = \frac{\sqrt{R^2 + 1}\, \ln \left[(1 - S) / (1 - RS) \right]}{(R - 1) \ln \left[\dfrac{2 - S(R + 1) - \sqrt{R^2 + 1}}{2 - S(R + 1) + \sqrt{R^2 - 1}} \right]}$$

Where, $$S = \frac{t_2 - t_1}{T_1 - t_1} \quad \text{and} \quad R = \frac{t_2 - t_2}{T_1 - T_2}$$

(7) Water thermal conductivity, k (BTU/hr ft °F)

$$K_k = 0.29738 + 7.7298 \times 10^{-4} T + 1.6439 \times 10^{-6} T^2 + 6.478 \times 10^{-10} T^3$$

with T in °F.

(8) Water dynamic viscosity (lb – ft/hr).

$$\mu = \frac{9.1379}{1 + 0.02918\, T + 1.448 \times 10^{-4}\, T^2}$$

with T in °F.

4 – RESULTS AND DISCUSSION

Five cases have been analyzed as shown in Table I. In all cases the following thermal hydraulic conditions were kept constant:

- cooling water inlet temperature: 70 °F
- equivalent mass of water in the loop: 6000 lb
- mass flow rate through test section: 80000 lb/hr

Notice that a fraction of the flow that leaves the test section goes to the heat exchanger while the rest is deviated through the bypass.

The heat exchanger has a partition of four chamber for the cooling water so that it is possible to use a limited number of tubes for partial power. For example, one can use 25 tubes for full power 1000 Kw and 5 tubes for low power (200 Kw).

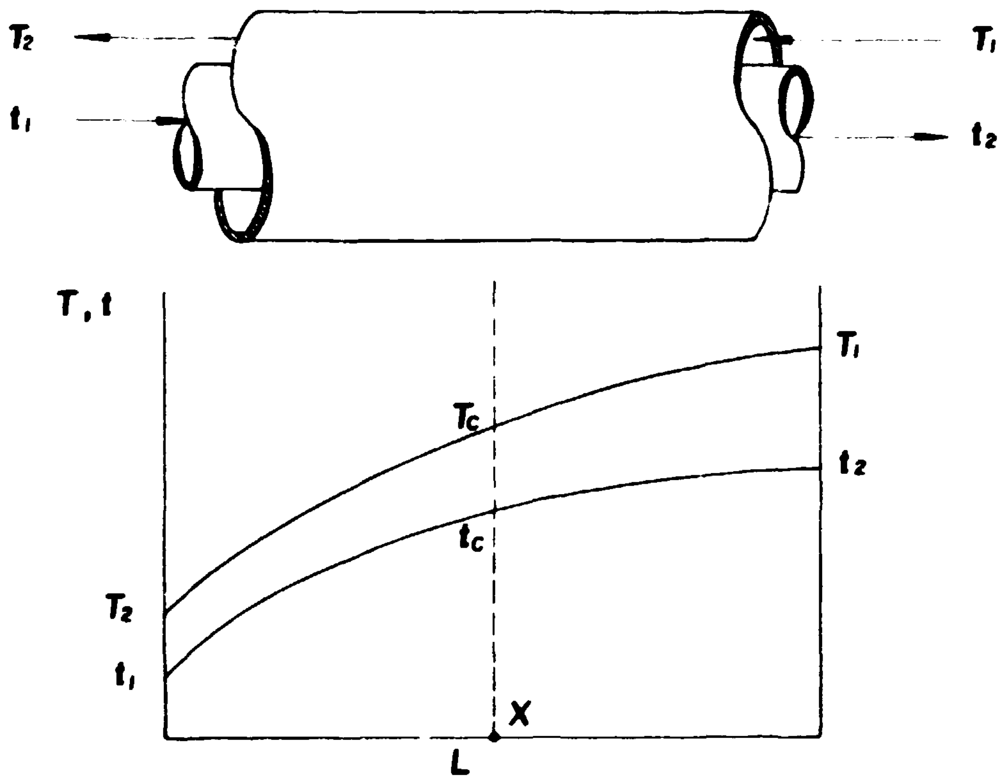

Figure 2 – Temperature distribution in single-pass counter flow heat exchanger.

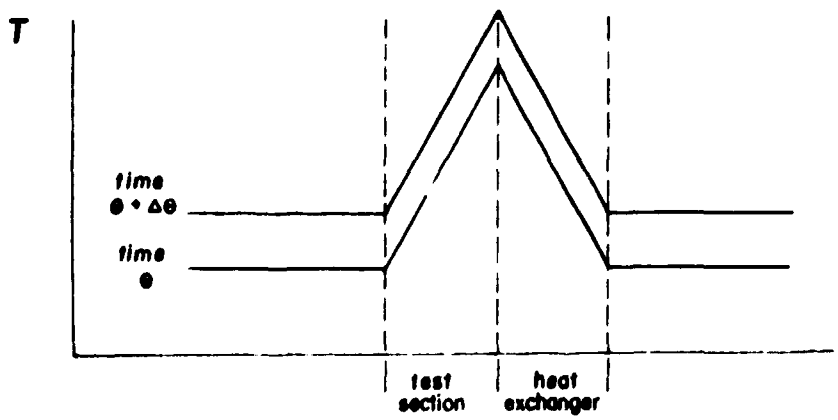

Figure 3 – Temporal variation of temperature in the loop.

Table I

Cases Analyzed

Case	Number of tubes used	Type of Process	Shell Side mass rate of flow lb/hr	Tube Side mass rate of flow lb/hr	Number of Steps	Potência Total kW	Remarks
1	5	heating up	18.000	20.000	1	200	
2	5	heating up	10.000	8.000	1	200	
3	25	heating up	18.000	30.000	1	1.000	
4	25	cooling down	18.000	30.000	1	1.000	Steady State
							Power before
							cooling 1000 kW
5	25	heating up	18.000	30.000	6	1.000	1st Step 195 kW
							2nd Step 390 kW
							3rd Step 512 kW
							4rh Step 680 kW
							5rh Step 850 kW
							6rh Step 1000 kW

Cases 1 and 2 show the influence of the heat exchanger mass flow rate in the dynamic response of the loop for a given power change. In both cases the power is raised in a single step to 200 Kw. In case 3 the flow conditions are the same of Case 1 but the power level is 1000 Kw. Figure 4 shows the loop temperature time dependence for these cases. Notice that the higher the flow rate and the power step the shorter the time to reach stationary conditions. This is a consequence of the nonlinear nature of the problem.

Case 4 represents a cooling situation where the power is decreased from 1000 Kw to zero in a single step.

Figures 5 to 7 show the time behavior of the temperature time derivative for cases 1 to 4. In all these situations the value of $dT/d\theta$ is well over the recommended limit value of 100 °F/hr. for a long period. Therefore we have to proceed on a step by step power increase. One possible way is the procedure used in Case 5, as shown in Fig. 8. By that, $dT/d\theta$ stays always within the limit, as illustrated in Fig. 9.

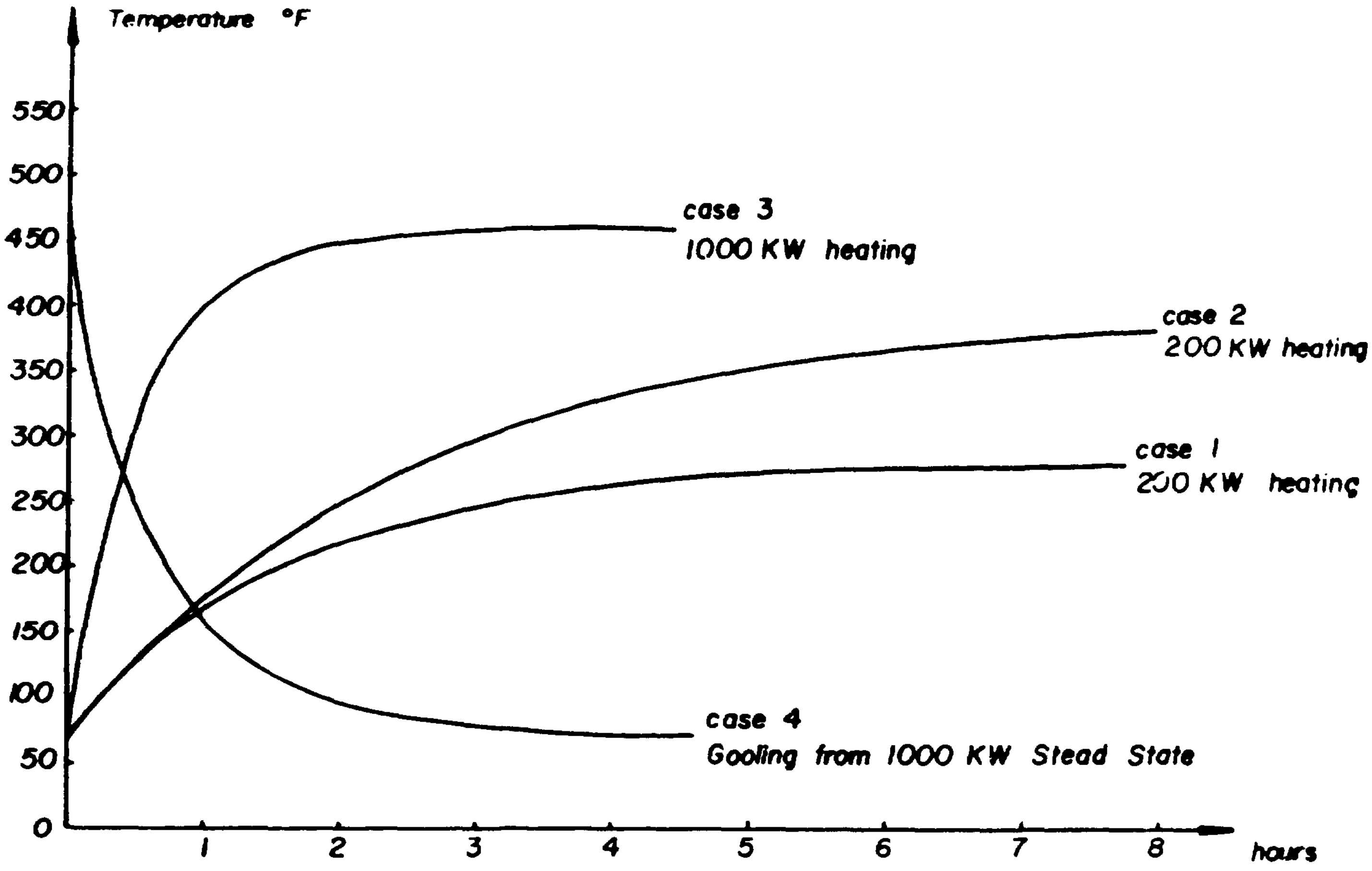

Figure 4 – Variation of outlet test section temperature with time for cases 1, 2, 3, 4.

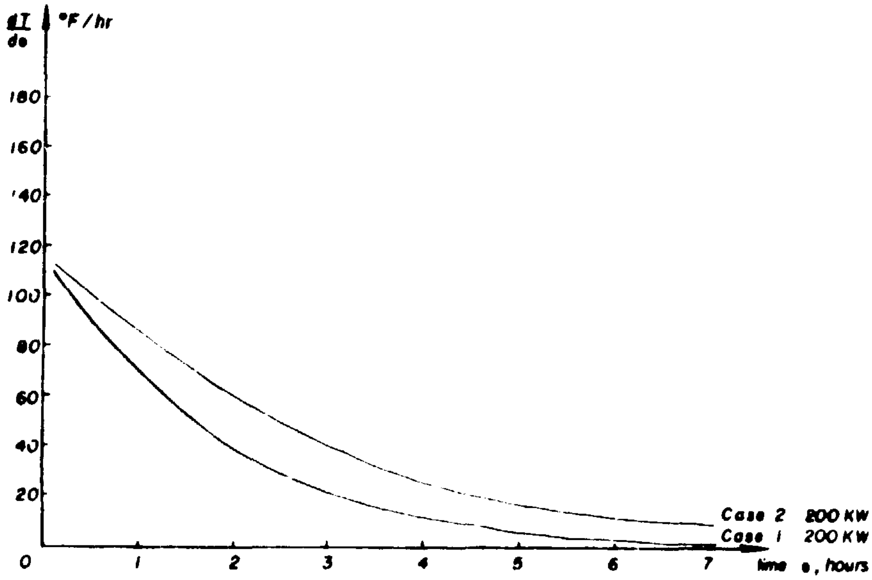

Figure 5 – Variation of $\frac{dT}{d\theta}$ with time case 1 & 2.

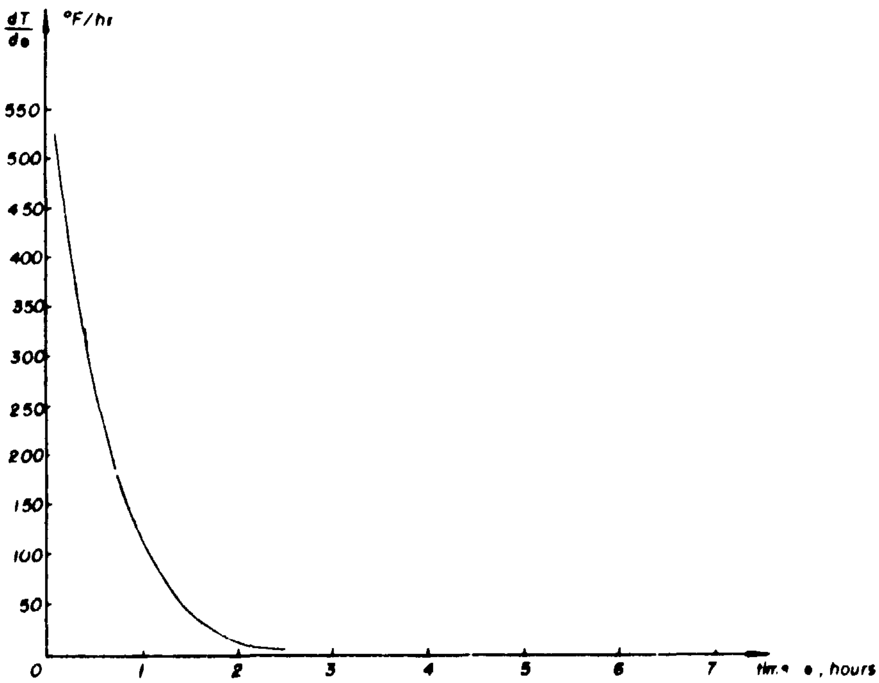

Figure 6 – Variation of $\frac{dT}{d\theta}$ with time case 3.

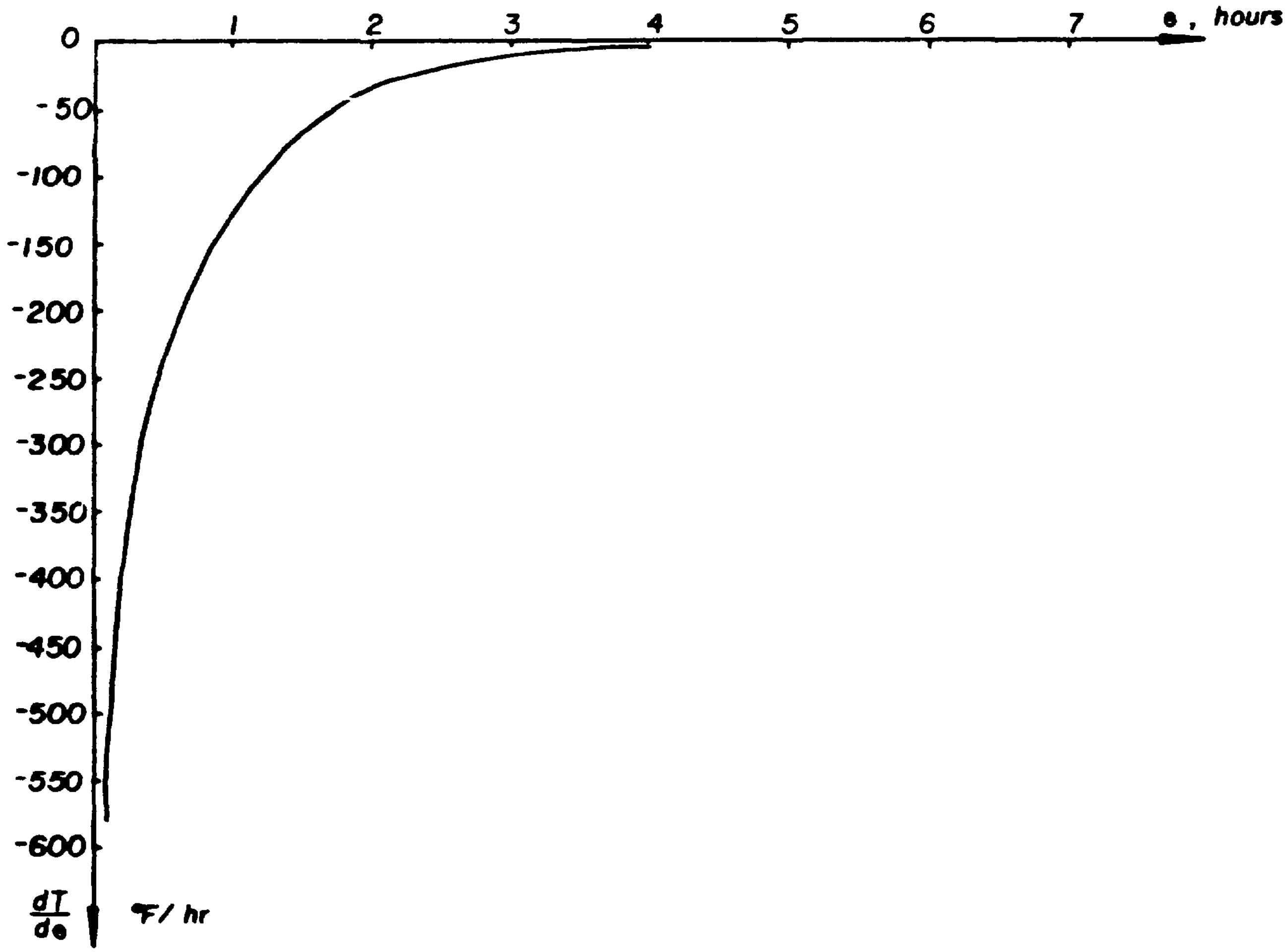

Figure 7 – Variation of $\frac{dT}{d\theta}$ with time case 4.

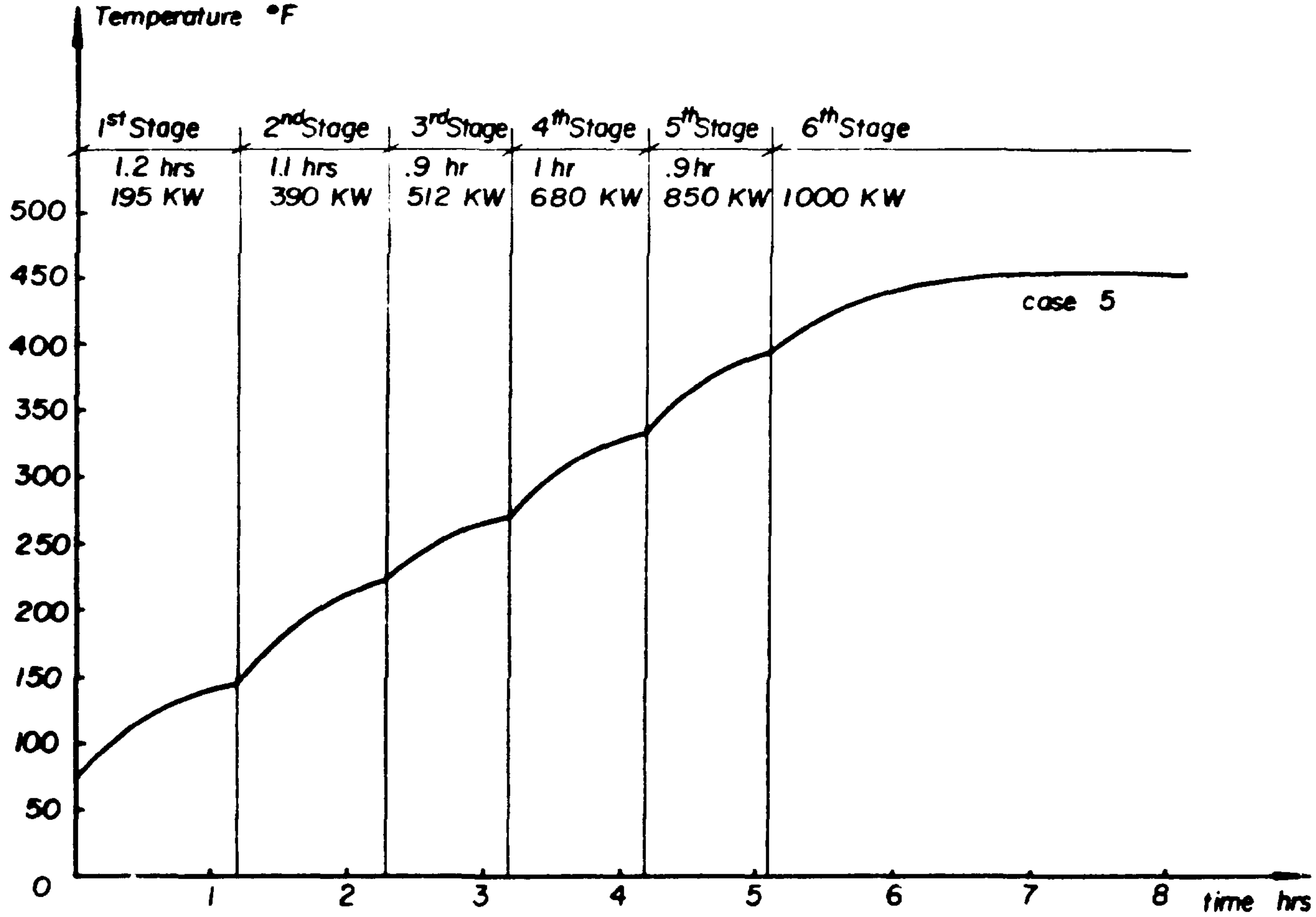

Figure 8 – Variation of outlet test section temperature with time for case 5.

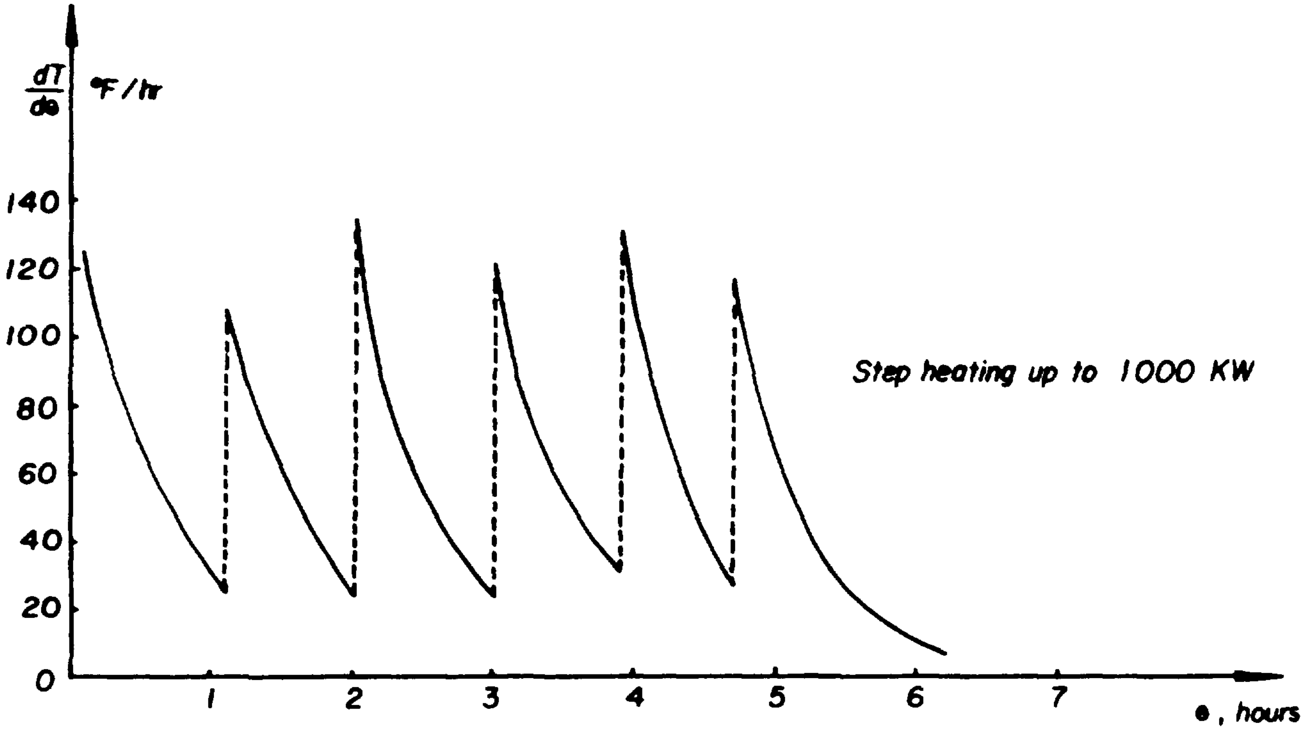

Figure 9 – Variation of $\frac{dT}{d\theta}$ with time case 5.

RESUMO

Desenvolveu-se um modelo matemático para a análise do comportamento térmico do circuito experimental de Água do I.P.E.N. durante mudanças de potência na secção de teste. Para uma dada temperatura de operação, pode-se estimar a potência necessária na secção de teste, bem como as condições de vazão no resfriador. Pode-se, ainda, determinar as máximas taxas de aquecimento ou resfriamento, para prevenir contra choques térmicos na tubulação e componentes. (autor)

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2. KERN, D. Q. *Process heat transfer.* New York, N.Y., McGraw-Hill, 1950.

(*) Bibliographic references related to documents belonging to IPEN Library were revised according with NB 66 of Associação Brasileira de Normas Técnicas.

NOMENCLATURE

A	heat exchanger total heat transfer area.
c_{ps}	shell side water specific heat.
c_{pt}	tube side water specific heat.
D	diameter.
F_t	ratio of the heat exchanger true temperature difference to the LMTD.
h_i	tube side heat transfer coefficient.
h_s	shell side heat transfer coefficient.
H	pump head.
k	water thermal conductivity.
M	loop water inventory.
P_{rs}	Prandtl number on shell side
P_{rt}	Prandtl number on tube side
Q	pump volumetric flow rate
Q_A	heat added to test section
Q_R	heat removed in heat exchanger
t_1	heat exchanger cold side inlet temperature
t_2	heat exchanger cold side exit temperature
t_c	heat exchanger cold side caloric temperature
T_1	heat exchanger hot side inlet temperature
T_2	heat exchanger hot side exit temperatue
T_c	heat exchanger hot side caloric temperature
T_{IN}	test section inlet temperature
U	overall heat transfer coefficient
W_s	shell side mass flow rate
W_t	tube side mass flow rate
μ	water dynamic viscosity
θ	variable time

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