PRELIMINARY THERMAL DESIGN OF A PRESSURIZED WATER REACTOR CONTAINMENT FOR HANDLING SEVERE ACCIDENT CONSEQUENCES

A.M. ABDULLAH, A. KARAMELDIN
Reactors Department,
Nuclear Research Centre,
Cairo, Egypt

Abstract

A one-dimensional mathematical model has been developed for a 4250 MW(th) Advanced Pressurized Water Reactor containment analysis following a severe accident. The cooling process of the composite containment-steel shell and concrete shield- is achievable by natural circulation of atmospheric air. However, for purpose of getting higher degrees of safety margin, the present study undertakes two objectives : (i) Instalment of a diesel engine-driven air blower to force air through the annular space between the steel shell and concrete shield. The engine can be remotely operated to be effective in case of station blackout, (ii) fixing longitudinally plate fins on the circumference of the inside and outside containment steel shell. These fins increase the heat transfer areas and hence the rate of heat removal from the containment atmosphere. In view of its importance - from the safety view point - the long term behavior of the containment which is a quasi-steady state problem, is formulated through a system of coupled nonlinear algebraic equations which describe the thermal-hydraulic and thermodynamic behavior of the double shell containment. The calculated results revealed the following : (i) the passively air cooled containment can remove maximum heat load of 11.5 MW without failure, (ii) the effect of finned surface in the air passage tends to decrease the containment pressure by 20 to 30%, depending on the heat load, (iii) the effect of condensing fins is negligible for the proposed fin dimensions and material. However, by reducing the fin width, increasing their thickness, doubling their number, and using a higher conductive metal than the steel, it is expected that the containment pressure can be further reduced by 10% or more, (iv) the fins dimensions and their number must be optimized via maximizing the difference or the ratio between the heat removed and pressure drop to get maximum heat flow rate.

1. INTRODUCTION

One of the severe accident category - beyond design basis accident - is core meltdown which may take place following a loss of coolant accident (LOCA), where the emergency core cooling system (ECCS) malfunctions or fails to refill the reactor core. This type of accident is normally followed by dangerous consequences like steam explosion and hydrogen deflagration or detonation, where the containment pressure may rise beyond its design value (e.g. 15 bar). These effects might cause failure of the reactor containment followed by the release and diffusion of radioactive fission products into the environment thereby threatening the public safety.

Since the containment represents the final barrier confining the aerosol and noble gases it is very important to have a good designed containment at least adequate to mitigate those consequences. For this purpose the present study undertakes two objectives: (i)presenting a preliminary thermal design analysis for the containment of a pressurized water reactor, (ii)proposing some modifications to the current design containments for mitigating the consequences of the accident under consideration.
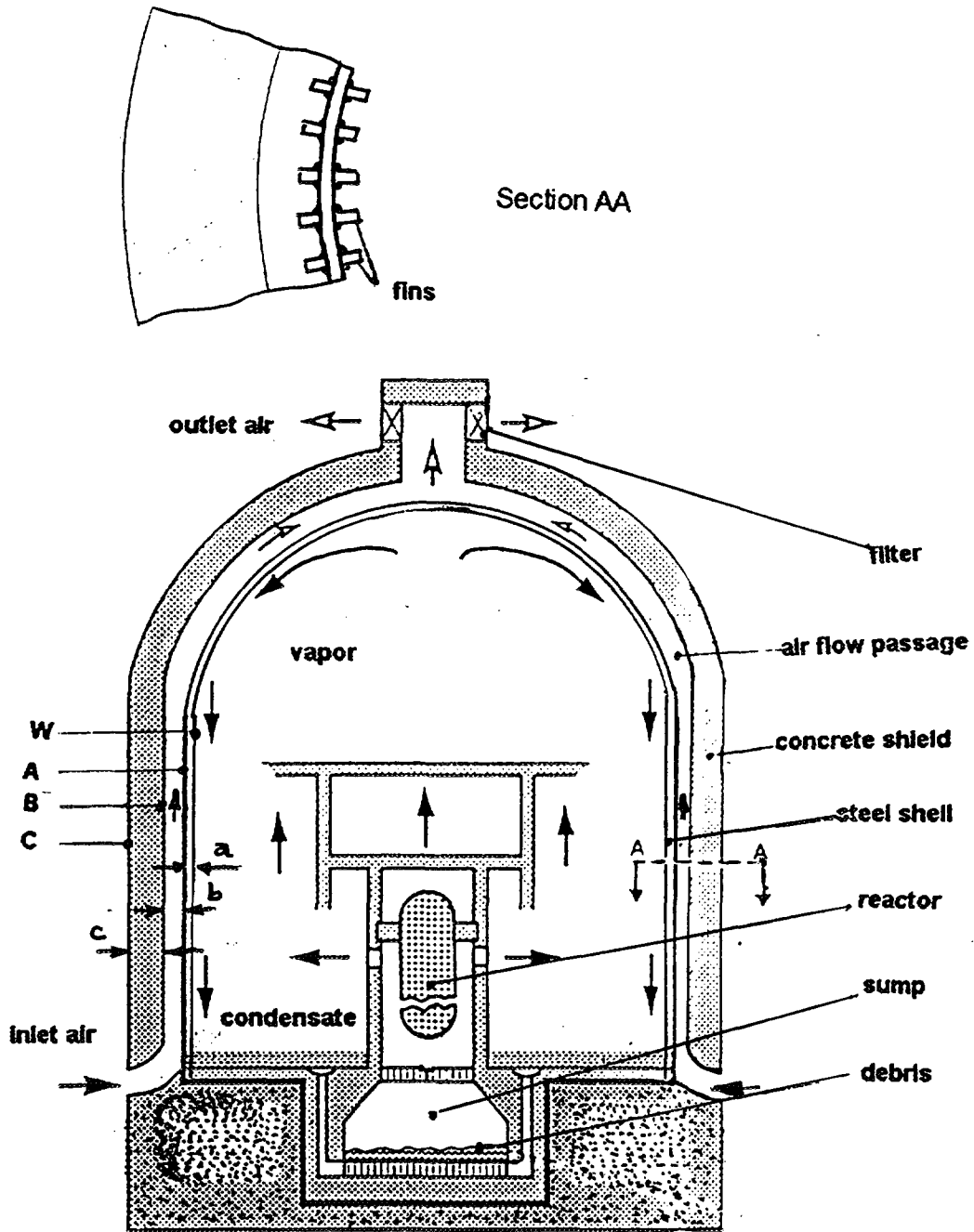
Figure (1) Illustrative figure of a passive containment after a postulated severe accident.

The present analysis is applicable to the today's double containment design. This composite containment, as shown in Fig.(1), consists of an inner steel shell 60 m diameter, 40 mm wall thickness, and reinforced concrete shield 2 m wall thickness. The annular gap between the two shells - which is about 80 cm width - represents a flow passage for atmospheric air. Thus the decay heat removal from the containment is based on a passive mechanism (e.g natural convection). However for getting higher degrees of safety, a diesel engine-driven air blower can be installed to force air through the annular space between the steel and the concrete shield. The engine which is energized by d.c. batteries can be remotely operated so that to be effective in case of station blackout. The free or forced air flow extracts the decay heat from the outside surface of the

steel containment and transfers it by convection to the air passage and by radiation to the concrete shield where the latter dissipates the heat to the atmospheric air.

Several designs and computer codes for severe nuclear reactor accident containment analysis have been developed [1,2,3,4]. The CONTAIN integral analysis code [1,2] was used for studying the long-term thermal hydraulic conditions after a severe nuclear accident in a PWR where the characteristic time constant is on the order of days. Consequently, the post accident period which continues several weeks must be analyzed to calculate the time behavior of the containment thermodynamic variables (e.g. pressure, temperature, mass fractions of non-condensible gases, etc.) So CONTAIN code therefore needs a long computing time for covering such long problem times. This is because the code uses calculational time-step size on the order of seconds to deal with the modeling approach used. So it is not practical to use CONTAIN code for parametric and conceptual studies as they are needed during the early design phase of future containment. Therefore, the simplified computer code TPCONT was developed for calculating the containment thermal-hydraulic conditions[3]. The advantage of this code is that the CPU time needed for a typical calculation over 40 days of problem time is 1 minute as compared with 5 hours, the time needed by CONTAIN. However, TPCONT has some uncertainties which need verification by experiments or by more detailed codes.

Another one-dimensional computer code PASCO has been developed [4], for predicting the thermal-hydraulic behavior of a reactor containment cooled by natural convection and to evaluate the experimental results obtained from PASCO test facility [5]. Good agreement between the measured and calculated variables(e.g. temperatures and air flow rates) has been obtained. However no comparison has been made between PASCO and the aforementioned codes.

In the present study the current design containment is modified in such a way that to permit forcing air-by a blower driven by diesel engine-inside the annular space between the two containments. To reduce effectively the containment pressure the steam condensation on the surface can be much enhanced by fixing highly heat conducting plates around the periphery of the steel containment. These plates act as fins to increase the condensation surface area. For plates 40 m high,50 cm width, and 0.5 m spaced, their total surface area may reach the cooled containment surface area. The plates act also as supporting or reinforced stays to the steel containment. Also it is possible to support longitudinal metallic plate fins on the periphery of the outside surfaces of the steel containment and concr te shield. For this purpose a one dimensional mathematical model has been developed for a PWR containment analysis following a severe core melt accident.

2.THE CONSEQUENCES FOLLOWING THE ACCIDENT

Current PWR plants have not been designed to withstand core meltdown and the ensuring accident events. Following the accident, the consequences may embrace some physical and mechanical processes. During the early period, which lasts about few hours after accident initiation, transient events likes blowdown, pressure vessel failure, steam explosion and hydrogen combustion or detonation may occur. The latter process may be followed by sudden and heavy load exerted onto the containment structure. The consequence would be mechanical failure (major leakage) of the containment and release of gases carrying radioactive materials into the environment . A very essential criterion for a future containment design must be the capability of the containment to resist the above mentioned process without failure.

3.MATHEMATICAL MODEL

In this study a one-dimensional mathematical model is adopted to describe the thermal and hydraulic processes which occur across the containment surfaces and the fluids boundary layer(condensate film and cooling air). After the occurrence of the accident the debris in the containment sump generates steam. Part of this steam condenses on the containment internal structure, steel installations, and the containment steel shell, while the rest accumulates gradually. Since the steel has relatively low heat capacity, high thermal conductivity and small volume (500 m³), its temperature reaches the saturation condition in a few hours. As for the concrete internal structure, where it has low thermal conductivity and high heat capacity and large volume (13,200 m³), it is heated slowly, as compared with containment atmosphere, and still absorbs heat for a relatively long period (about 10 days) until it reaches a thermal equilibrium state with the containment atmosphere. At this time the internal concrete no longer absorbs heat with the result that approximately all the steam produced by decay heat -under certain equilibrium case- condenses on the containment steel surface and transmitted by the air. This represents the maximum rate of heat which can flow through the containment steel shell. From the view point of containment safety the time period preceding the equilibrium state (t<10 days) is not serious although the decay heat varies between 91.6 to 11.5 MW, and that the heating rate of internal concrete is about 20 °C per day. On the other hand the next period (t>10 days) is less safe. Since, the containment atmosphere pressure and temperature remain relatively high for a long period where the cooling rate is about 1°C /day. Thus any disturbance in the thermodynamic conditions of containment (e.g. hydrogen combustion, temperature rise in the atmospheric air or partial blocking of the air passage exit) may produce dangerous unsafe conditions. Based on the above discussion, the present study is therefore focused on the important long term period which comes after attainment of the equilibrium state between the containment vapor and internal structures (i.e for t>10 days). Therefore this system is treated as a quasi-steady state problem as described by the following equations.

3.1.Overall Heat Balance Inside The Containment

It is assumed that the containment water, atmosphere, and internal structure are at saturation conditions. Thus in the final steady-state case inside the containment the decayed heat is transferred to water present in the sump as a latent heat of vaporization. Meanwhile a part of produced vapor condenses and transfers its latent heat to the internal steel surface. The overall heat balance is as follows :

$$Q = A \cdot F \cdot F_1 \cdot h \cdot (T_{sat} - T_w) \qquad . \qquad (1)$$

where F_1 is a factor of condensation heat transfer reduction due to presence of air with steam and can be determined [6] from the following equation :

$$F_1 = 0.4254 *(\frac{m_a}{m_v})^{-0.573} \qquad if\, (\frac{m_a}{m_v}) \leq 0.05$$

$$= 0.17 \qquad . \qquad if\, (\frac{m_a}{m_v}) > 0.05$$

$$A.F = \eta \cdot A_f + A \qquad .$$

and F is a factor of area increase due to the presence of the fins
where η is the fins efficiency and A_f is the fins area[7].
h can be determined from McAdams filmwise condensation over a vertical plate

$$h = 1.13 * [\frac{g \cdot \rho_l \cdot (\rho_l - \rho_v) \cdot h_{fg} \cdot k_l^3}{\mu_l \cdot (T_{sat} - T_w) \cdot L_{eff}}]^{0.25}$$

and the steam mass can be determined as a function of state equation as follows:

$$P_v = \frac{m_v}{18} \cdot \frac{R \cdot T_{sat}}{V} \qquad . \qquad (2)$$

where m_v is the vapor mass and 18 is the water molecular weight.

The heat flow through the containment steel shell Q can be determined [8].
The only unknowns in the above equation are T_{sat} and T_w, considering that water and steam properties can be correlated as a function of mean film temperature. Also the steam pressure can be correlated as a function of saturation temperature.

Steel inner surface temperature can be determined from the following equations assuming that in the steady state the heat transferred from the condensation process is conducted through the steel shell.

3.2. Heat Conduction Through The Steel Shell :

The heat flow is conducted through the steel shell by conduction:

$$Q = \frac{2\pi \cdot k_s \cdot L_{eff}}{\ln((D+2a)/D)} \cdot (T_w - T_a) \qquad (3)$$

3.3. Heat Flow at Surface "A" :

The heat conducted through the steel shell is convected to the flowing air through the air passage and radiated to concrete surface b as follows :

$$Q = h_a \cdot F \cdot \pi \cdot (D+2a) \cdot L_{eff} \cdot (T_a - Tm)$$
$$+ \pi \cdot (D+2a) \cdot L_{eff} \cdot \frac{\sigma}{\frac{1}{\epsilon_a} + \frac{1}{\epsilon_b} - 1} \cdot (T_a^4 - T_b^4) \qquad (4)$$

where the convective heat transfer is experienced to be by turbulent forced convection:

$$h = \frac{k_a}{L_{eff}} * 0.1 \ (Gr \cdot Pr)^{\frac{1}{3}} \quad , \quad Gr = \frac{g \cdot \beta \cdot (T_a - T_m) \cdot L_{eff}^3}{v^2}$$

The air properties are taken at the mean film temperature and all air properties are correlated as functions in the temperature.

3.4. Flowing Air Momentum Equation :

The buoyancy driving pressure is equated with the pressure drop of inlet air, acceleration, diversion through the air passage, friction, and the outlet pressure drops. It is assumed that the inlet and outlet manifolds are smooth. Therefore the momentum equation can take the following form :

$$g \cdot L_{eff} \cdot (\rho_{ain} - \rho_m) = \frac{1}{2} \rho_m \cdot U^2 \cdot [2 + \frac{0.1364 * L_{eff}}{D_h * Re^{\frac{1}{4}}}] \qquad (5)$$

The air properties can be correlated as functions in the temperature, reducing the unknowns to T_m and U.

3.5. Heat Balance in The Air Passage :

The heat convected from surfaces "A" and "B" increases the air energy content. The equation describing the passage air heat balance is as follows :

$$\rho_m \cdot U \cdot \frac{\pi}{4} \cdot [(D+2a+2b)^2 - (D+2a)^2] \cdot (T_m - T_{ai}) =$$
$$h_a \cdot F \cdot \pi (D+2a) \cdot L_{eff} (T_a - T_m) + h_b \cdot \pi \cdot (D+2a+2b) \cdot L_{eff} (T_b - T_m) \qquad (6)$$

3.6. Heat Balance of The Concrete Shield "B" :

A part of the net heat radiated from surface "A" to surface "B" is convected to air flowing in the air passage. Meanwhile the rest is conducted to the surface "C" as shown below :

$$\pi \cdot (D+2a) \cdot L_{eff} \cdot \frac{\sigma}{\frac{1}{\epsilon_a} + \frac{1}{\epsilon_b} - 1} \cdot (T_a^4 - T_b^4) =$$

$$h_b \cdot \pi \cdot (D+2a+2b) \cdot L_{eff} \cdot (T_b - T_m) + \frac{2 \cdot \pi \cdot k_c \cdot L_{eff}}{\ln \frac{D+2a+2b+2c}{D+2a+2b}} \cdot (T_b - T_c) \qquad (7)$$

Finally the heat conducted through the concrete shield is convected to the ambient air as given below :

$$\frac{2 \cdot \pi \cdot k_c \cdot L_{eff}}{\ln \frac{D+2a+2b+2c}{D+2a+2b}} \cdot (T_b - T_c) = h_c \cdot \pi \cdot (D+2a+2b+2c) L_{eff} \cdot (T_c - T_{ai}) \qquad (8)$$

The above eight equations contain eight unknowns namely T_{aat}, T_w, T_a, T_m, T_b, T_c, m_v and U. These equations have been solved numerically to calculate the above unknowns.

4. Results and Discussion

The present work aimed to reinforce the containment engineering safety features. This is available through a smart design to enhance the performance
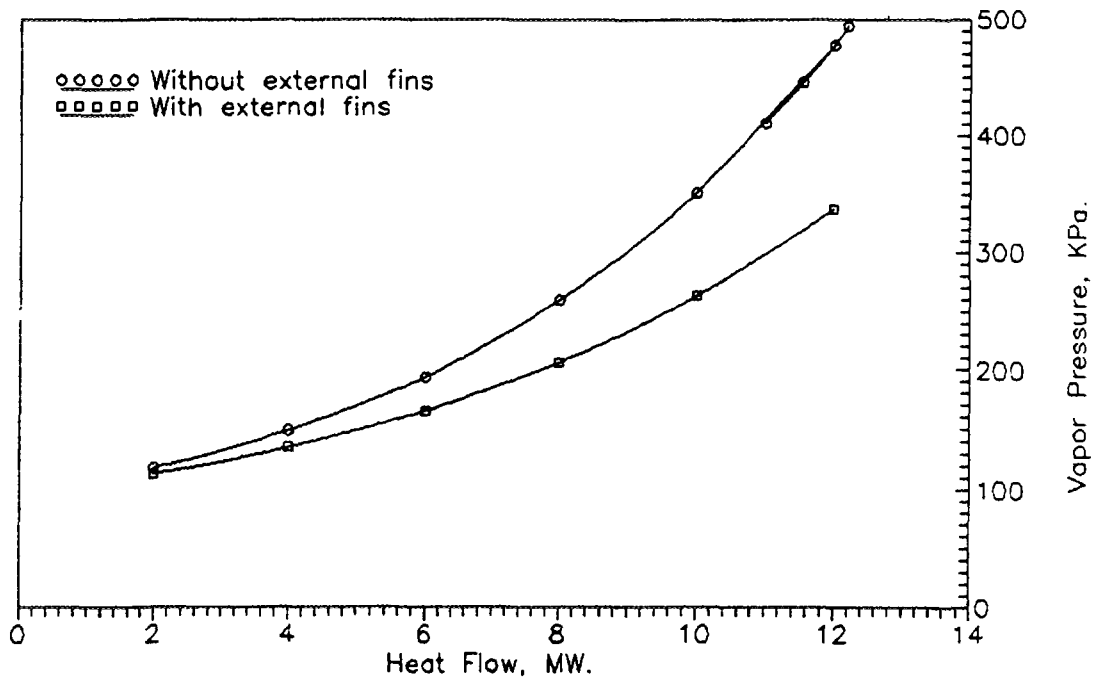
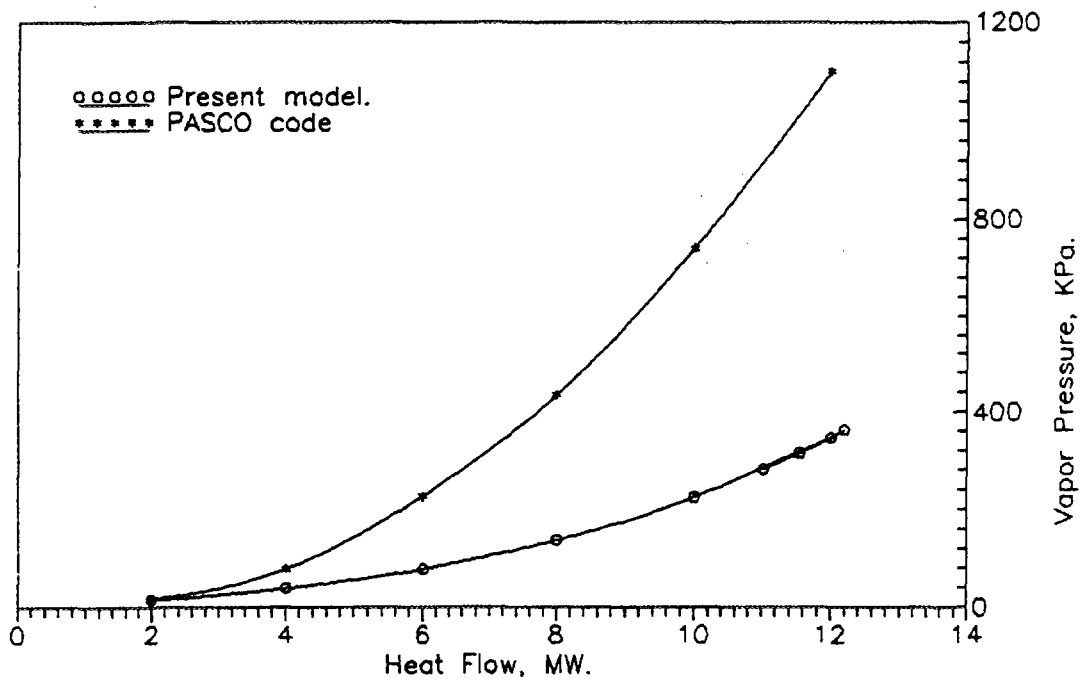*Figure (2) Passive Containment Total Pressure with Removable Heat Load Variation with Fins Presence.*

Figure (3) Passive Containment Vapor Pressure with Removable Heat Load (without Air Filtering).
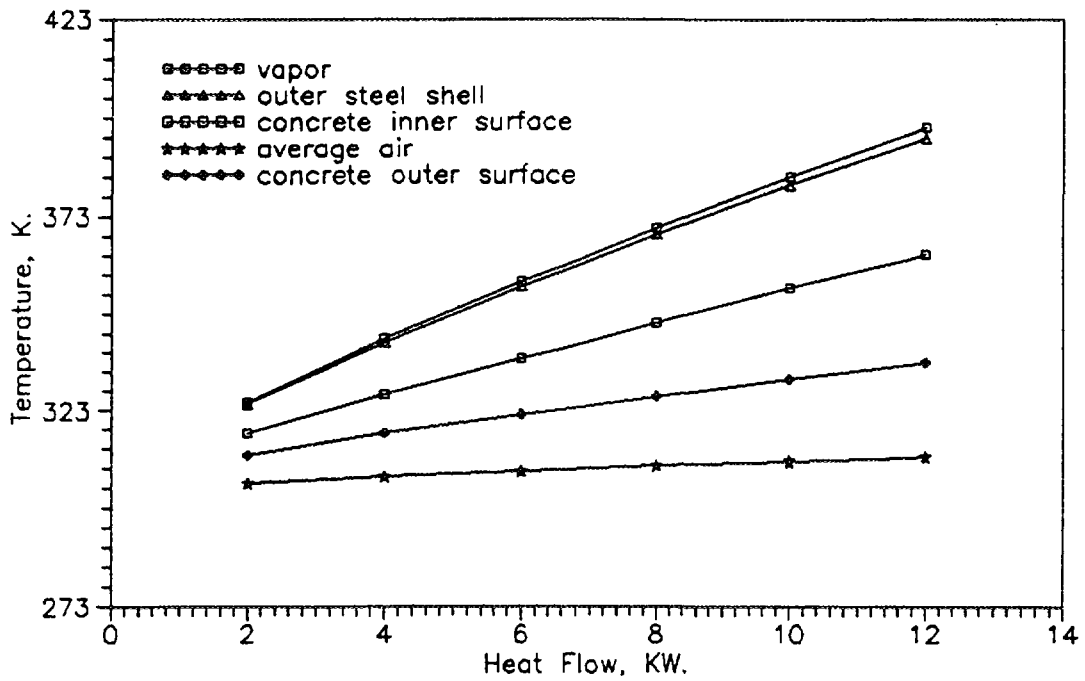
Figure (4) *Passive Containment Temperature Distribution (with external fins)*
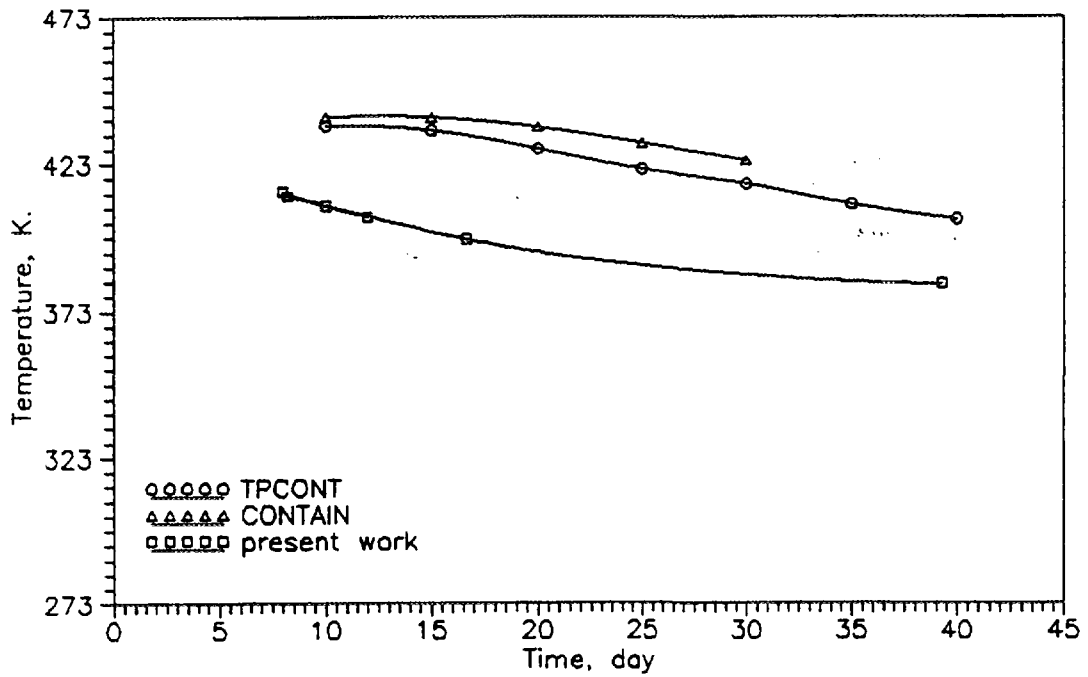

Figure (5) *Comparison Between Different Containment Codes Temperatures and The Present Model.*

of the double passive containment natural heat circulation after a postulated severe accident. The proposed design enhancement is to substitute the weakness of bad heat transfer coefficient of the flowing air by increasing the effective heat transfer area on the outer side of the containment steel shell. A simple one-dimensional mathematical model was employed and compared with by other works to stand up the validity of this model. Hence a comparison between the finned and unfinned outer steel shell was made.

The results presented here are based on the containment data reported in ref. 3 and 4. The system of the nonlinear algebraic equations derived , have been solved simultaneously for the unknown variables. The thermophysical properties of air and condensate film have been expressed analytically in terms of their respective temperatures. Due its importance as justified before at the beginning of the text, we are interested in the long term thermal-hydraulic and thermodynamic behavior of the containment. First, the effect of the longitudinally supported steel fins on the containment steel shell is investigated. The results -which are based on fin dimensions of 40 m height, 0.5 m width, 0.002 m thickness, and 0.5 m spaced- showed that the effect of external fins, which are supported on the outer surface of the containment steel shell, tends to reduce the containment pressure by about 20 to 30% as can be seen from Fig.(2), where the rate of pressure reduction increases with the removed heat load. On the other hand the calculated results revealed that the internal condensing fins have negligible effect due to the highly steam condensation coefficient. However, it is expected that these fins can be more effective if their number is doubled, i.e. 0.25 m spaced, with 0.25 m width, 0.04 m thickness, and made of a higher conductive material than steel. Fig.(3), shows the variation of the containment pressure with the removable load -which was taken as input variable- as compared with PASCO code. It can be seen that the differences between the two sets of results are relatively large. The higher pressure values of PASCO may be attributed to its low values of the air stream velocity (e.g. about 0.8 m/s). This diminishes the cooling rate of the containment atmosphere, thereby reducing the rate of pressure decrease. The variation of temperature distribution across the composite containment with the removable heat load is depicted in Fig.(4). These results are based on a finned surface in the air flow passage. It can be seen that the containment steel shell temperature reaches about 125 °C. The corresponding temperature without fins can be calculated to be 130 °C. These values correspond to a maximum heat flow of 11.5 MW as calculated in ref.[5]. The corresponding containment pressures are 4 and 5 bar respectively, which demonstrates that the fins reduce the containment pressure by about 20%. Finally, Fig.(5) shows the containment atmosphere temperature as compared with the TPCONT and CONTAIN codes. It can be seen that the higher temperatures detected by these codes may be attributed to the filters installed into the air pass during these codes calculations.

NONEMCLATURE

a   =containment steel shell thickness(m).
b   =air passage width (m)
c   =concrete shield thickness(m).
c_p =specific heat(J/Kg.°K).
D   =containment diameter(m).
F   =factor of non condensible gases on heat transfer coefficient.
Gr   =Grashoff number.
h   =enthalpy(KJ/Kg), also heat transfer coefficient(W/m².°K).
K   =thermal conductivity(W/m.°K).
L   =containment height(m).
L_{eff}=containment effective height(L+D/2) (m).
m   =mass flow rate(Kg/s).

n   =number of plate fins.
n_v =number of vapor moles.
P   =pressure(KPa).
Pr   =Prandtl number.
Q   =thermal power(W).
T   =temperature($^\circ$K).
t   =time(s), also fin thickness(m).
U   =velocity(m/s).
V   =containment free volume(m^3).

Greek Symbols

β = coefficient of thermal expansion($^\circ$K^{-1}).
η = fin efficiency
μ =dynamic viscosity(Kg.s/m^2).
ν =kinematic viscosity(m^2/s).9
ρ =density(Kg/m^3).
σ =Stefan-Boltzman constant(W/m^2.$^\circ$k^4).

Subscripts

a   =outside containment steel hull wall, also air.
ai   =input air.
b   =inside surface of concrete shield.
c   =outside surface of concrete shield.
l   =condensate.
m   =mean value.
s   =steel.
sat =saturation condition.
v   =vapor.
w   =inside containment steel shell surface.

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