Thermal Analysis of Chimneys by Finite Element

Bashar Faisal Abdul Kareem (Asst.Lecturer)

Abstract

The study is concerned with effect of thermal stresses on chimneys, where the thermal loads considerate are based on actual field measurements of temperature variation in Al-Dora chimney- Baghdad. These temperature variations are divided into two parts:

1- Uniform heating.
2- Temperature gradient across the thickness of chimney shell due to flue gases.

Thermal analyses were carried out using ACI-307-08 provisions, and STAAD.Pro-V8i using (3D – plate element).

Comparison studies in thermal analyses were made on four chimneys similar in dimensions, but different in materials, (Reinforced Concrete, Steel, Stainless Steel, and Aluminum). It was found that the metal chimneys give higher results in radial and vertical displacements, while higher results in the bending moments and membrane stresses were found in the reinforced Concrete chimney.

Thermal analyses were carried out to study the effect of chimney shell thickness. It was found that the reactions at the base of the chimney are proportional to the thickness of the shell, but the radial and vertical displacements are inversely proportional with the thickness of the shell. While the effect of changing thickness on the bending moments and membrane stresses was found to be small which indicates that increasing the thickness of shell chimney doesn’t lead to smaller thermal stresses. Finally, it was found that the Uniform heating component is more effective on the bending moments, membrane stresses and vertical displacements, while the rotations were not affected much by thermal loads. Winter time is found to be more critical since it gives higher temperatures gradient.

Keywords: Thermal analysis, Chimney, Finite Element
Symbols:

\[ r_q = \text{Ratio of heat transmission through chimney to lining} = 0.5; \]
\[ t = \text{Thickness of chimney shell.} \]
\[ t_s = \text{Thickness of air space or insulation.} \]
\[ t_b = \text{Thickness of lining, (in).} \]
\[ T = \text{Maximum temperature of gas inside chimney.} \]
\[ T_o = \text{Minimum temperature of outside air surrounding chimney.} \]
\[ C_c = 12(\text{Btu-in.)/(h-ft}^2\cdot \text{°F}) \text{ of thickness/h°F difference in temperature for concrete.} \]
\[ C_s = \text{to be obtained from the manufacturer of the materials used;} \]
\[ C_u = \text{to be obtained from the manufacturer of the lining materials used.} \]
\[ D_{bi} = \text{Inside diameter of lining.} \]
\[ D_b = \text{Mean diameter of lining.} \]
\[ D_s = \text{Mean diameter of space between lining and shell.} \]
\[ D_{ci} = \text{Inside diameter of chimney shell.} \]
\[ D_c = \text{Mean diameter of chimney shell.} \]
\[ D_{co} = \text{Outside diameter of chimney shell.} \]
\[ \alpha = \text{Thermal expansion coefficient.} \]
\[ \text{SQX, SQY = Shear stresses (Force/ unit len./ thk.)} \]
\[ \text{SX, SY, SXY = Membrane stresses (Force/unit len./ thk)} \]
\[ \text{MX, MY, MXY = Moments per unit width (Force x Length/length)} \]

1. Introduction

Chimneys are used in power plants for venting hot flue gases or smoke to the outside atmosphere. In recent years, the height of power plant concrete chimneys has increased to enhance the draw of air for combustion and to disperse pollutants over a greater area to reduce pollutant concentrations. While the number of reported chimney collapses due to an internal fire is very small, the consequences of chimney damage could be costly in terms of economic and human loss. The popularity of fiberglass reinforced plastic (FRP) liners – which are combustible materials – has made the risk of a fire in tall chimneys even more relevant in recent years. The FRP liners are used in reinforced concrete chimneys to protect the chimney shell from the effect of hot flue gases. Some of the possible sources of ignition in chimneys with FRP liners can be hot work inside the chimney during FRP installation or maintenance, ignition of stored
flammable materials at the base of the chimney, ignition inside the flue gas desulfurization system or other equipment upstream of the chimney.

A critical effect of an uncontrolled fire in a chimney is the reduction in concrete strength [1], which leads to a decrease in the chimney load carrying capacity and service life. At an elevated temperature, the concrete experiences a variety of chemical and physical changes. For example, large volume changes resulting from non-uniform thermal expansion of aggregates and shrinkage of the cement paste, results in cracking and spalling. Spalling which is usually explosive and critical for structural integrity, is induced by mechanical and thermal stresses and pore pressure [2]. Spalling generally occurs at high temperatures, even though it is also observed at temperatures as low as 200 °C [3]. For spalling to occur, there needs to be a minimum moisture content as well as a temperature gradient of approximately 5–8 K/mm [1]. Temperature gradients induced by heating or uncontrolled fire depend not only on the heating source temperature but also on the heating rate.

Types of chimneys:
A- Metal chimneys,( Shorter construction time, lower weight).
B- Concrete chimneys,( Lower cost if the raw materials are available).
   1. Unlined chimneys.
   2. Lined chimneys.
      Linings can be classified as:
         a- Independent like brick, concrete, insulated steel, insulated Stainless Steel, or insulated Aluminum.
         b- Corbel supported brick.
         c- Shotcrete.

1.1 Importance of chimney lining:
   - Unlined chimneys may leak harmful gases like carbon monoxide.
   - Lining reduces thermal stresses and the chance of fire.
   - Lining keeps the shell away from the chemical effect of flue and acids vapors.

1.2 Forces acting on chimneys:
The chimney shell shall be designed to resist stresses resulting from the weight of the chimney, the effect of temperature, both vertically and circumferentially, and the effect of either wind or earthquake, whichever is greater.
This paper gives a comparison studies in thermal analyses were made on four chimneys similar in dimensions, but different in materials, (Reinforced Concrete, Steel, Stainless Steel, and Aluminum), the effect of chimney shell thickness on thermal stresses, and the effect of removing the lining of chimney on thermal stresses.

2. Properties of steel under high temperature:

Jyri Outinen [4] studied the high-temperature behavior of structural steel S355 at elevated temperatures with 30 tensile tests. Test results were combined with an earlier test series that was carried out in the same laboratory. The mechanical properties of structural steel S355 determined from the transient state tests are illustrated in Figures 1 and 2.

![Fig.1](image1.png)  
**Fig.1** Yield strength of structural steel s355 at temp. 20℃-950℃

![Fig.2](image2.png)  
**Fig.2** Modulus of elasticity of structural steel s355 at temp. 20℃-950℃
The effect of heating rate which also affects the strain rate during tests was studied by carrying out transient state tests at a low stress level. Three different heating rates were used varying from 10°C/min to 30°C/min. Test results within these temperature rates for structural steel did not differ much from each other. The behavior of structural steel S355 analyzed on the basis of transient state test results seems to be very near the material model given in Eurocode 3: Part 1.2. It can be concluded that within the limits that are given for that model in Eurocode 3 (EC3), the use of it for structural steel S355 is well-grounded in structural fire design of steel structures.

3. Properties of concrete and reinforcing steel under high temperature:

Malhotra [5] studied the effect of water/cement ratio, state of stress and age on the compressive strength of concrete exposed to fire. He concluded that:

1. The effect of temperature on the compressive strength of concrete is independent of the water/cement ratio within the range normally used in its manufacture.
2. The aggregate/cement ratio has a significant effect on the strength of concrete exposed to high temperature, the proportional reduction being smaller for lean mix than for rich mixes.
3. During the period of heating, the concrete under a constant stress exhibits a smaller reduction in strength than the concrete under no stress.

Harda and Furumura [6] investigated the strength, elasticity and thermal properties of concrete subjected to evaluated temperatures. The results showed that both compressive strength and tensile strength to decrease as temperature increase. The compressive strength at 400 °C reaches about 60% of its initial value. The modulus of elasticity and thermal diffusivity decrease when temperature increases.

From the previous information, in general, the structural properties of concrete are reduced with increase of temperature except (α).

Fawaz in his study [8] concluded that:

1- \( E_c \) (the modulus of elasticity for concrete) decreases with increase in temperature, and by Nizamuddin (32):

For \( 0 \leq T < 630 ^\circ C \), \( E_c(T) = [1.0 - 0.001032(T)] \times E_{co} \) ..........................(1)

For \( T \geq 630 ^\circ C \), \( E_c(T) = 0.35 \times E_{co} \) .................................(2)

- 121 -
where $E_{co}$ is the value of $E_c$ at 0°C.

2- $f'_c$ (the compressive strength for concrete ) decrease with increase in temperature
For $0 \leq T < 350°C$, $f'_c (T)= f'_co$ .....................................(3)
For $T \geq 350°C$, $f'_c (T)= [1.0-0.0778(T-350)]x f'_co$ ...............(4)
where $f'_co$ is the value of $f'_c$ at 0°C.

3- $\alpha_c$ (the coefficient of thermal expansion for concrete):
Thermal expansion is a very important free strain associated with fire. It changes rapidly with temperature. Previous studies have shown an increase in thermal expansion with increase in temperature. The thermal expansion of concrete depends mainly on the thermal expansion of the cement paste and aggregate.
For $0 \leq T < 500°C$, $\alpha_c(T)=10.8x10^{-6}/c$ ............(5)
For $T \geq 500°C$, $\alpha_c(T)=16.2x10^{-6}/c$ ............(6)

4. **Thermal stress in cylindrical shells:**
1- Uniform temperature distribution [9]:
If a cylindrical shell with free edge undergoes a uniform temperature change, no thermal stresses will be produced. But, if the edges are supported or clamped, free expansion of the shell is prevented, and local bending stresses are setup at the edges. Knowing the thermal expansion of a shell when the edges are free, the values of the reactive moments and forces at the edges for any kind of symmetrical supported can obtained by using many equations given in this reference.

2- Temperature gradient in the radial direction [9]:
Assuming that $T_1$ and $T_2$ are the uniform temperatures of the cylindrical wall at the inside and outside surfaces, respectively, and that the variation of the temperature through the thickness is linear. In such a case at points at large distance from the ends of the shell, there will be no bending, and the stresses can be calculated by using the formula:
\[
\sigma_x=\sigma_\phi= \pm \frac{E \times (T_1-T_2)}{2(1-\mu)} \quad \text{............. (7)}
\]
Which was derived for clamped plates. Thus, the stresses at the outer and the inner surface are represented in this equation where the upper sign refers to the outer surface indicating that a tensile stresses will act on this surface if $T_1 > T_2$. 

- 122 -
Near the ends there will usually be some bending of the shell, for example Figure (3-a), it can be observed that at the edge, the stresses result in uniformly distributed moments M₀ of the amount

\[ M₀ = \frac{E₀(T₁ - T₂)}{12(1 - \nu)}h^2 \] ........................(8)

3- Temperature gradient in the longitudinal direction [9]:

If the temperature is constant through the thickness of the wall but varies along the length of cylinder, the problem can easily be reduced to the solution of the equation \( D \frac{d^4w}{dx^4} + \frac{E₀}{a^2}w = z \), let \( T = F(x) \) be the increase of the temperature of the shell from a certain uniform initial temperature and assuming that the shell is divided into infinitely thin rings by planes perpendicular to the x-axis and denoting the radius of the shell by a, the radial expansion of the rings due to the temperature change is \( \alpha a F(x) \). This expansion can be eliminated and the shell can be brought to its initial diameter by applying an external pressure of an intensity \( z \) such that:

\[ \frac{a^2z}{E₀} = \alpha a F(x) \] ..........................(9)

Which gives: 

\[ Z = \frac{E₀a}{\alpha} F(x) \] ..............................(10)

A load of this intensity entirely arrests the thermal expansion of the shell and produces in it only circumferential stresses having a magnitude:

\[ \sigma_θ = -\frac{az}{h} = -E\alpha a F(x) \] ..........................(11)

to obtain the total thermal stresses, one must superpose on the stresses of the last equation the stresses that will be produced in the shell by a load of intensity \( -z \).

5. Thermal analysis procedure of ACI-307 08:

According to the ACI-307 08 the chimney shell shall be designed to resist stresses resulting from the weight of the chimney, the effect of temperature, both vertically and circumferentially, and the effect of either wind or earthquake, whichever is greater.

5.1—Vertical temperature stresses

5.1.1 The maximum vertical stresses in the concrete and steel, \( f_{CTV}'' \) and \( f_{STV}'' \), in psi, occurring at the inside of the chimney shell due to temperature shall be computed by Eq. (12) and (13), respectively
\begin{align*}
    f_{CTV}'' &= \alpha t e \times c \times T x \times Ec \quad \ldots\ldots(12) \\
    f_{STV}'' &= \alpha t e (c - 1 + \gamma 2) \times TxnEc \quad \ldots\ldots(13)
\end{align*}

where

\begin{equation}
    c = -\rho n(\gamma 1 + 1) + \sqrt{[\rho n(\gamma 1 + 1)]^2 + 2\rho n[\gamma 2 + \gamma 1(1 - \gamma 2)]} \quad \ldots\ldots(14)
\end{equation}

and

\begin{equation}
    n = \frac{E_s}{Ec} \quad \ldots\ldots(15)
\end{equation}

The temperature gradient across the concrete shell, \( T_x \), shall be computed by Eq. (6-5) through (6-8), or by using a complete heat-balance study for all operating conditions.

a. For unlined chimneys

\begin{equation}
    T_x = \frac{t d c l}{C c \ d c} \left( \frac{T_i - T_o}{T_i - T_o} \right) \quad \ldots\ldots(16)
\end{equation}

b. For lined chimneys with insulation completely filling the space between the lining and shell

\begin{equation}
    T_x = \frac{t d b i}{C c \ d c} \left( \frac{T_i - T_o}{T_i - T_o} \right) \quad \ldots\ldots(17)
\end{equation}

c. For lined chimneys with unventilated air space between the lining and shell

\begin{equation}
    T_x = \frac{t d b i}{C c \ d c} \left( \frac{T_i - T_o}{T_i - T_o} \right) \quad \ldots\ldots(18)
\end{equation}

d. For lined chimneys with a ventilated air space between the lining and shell

\begin{equation}
    T_x = \frac{t d b i}{C c \ d c} \left( \frac{T_i - T_o}{T_i - T_o} \right) \quad \ldots\ldots(19)
\end{equation}

where:

\begin{itemize}
    \item \( r_q \) = Ratio of heat transmission through chimney to lining = 0.5;
    \item \( t \) = Thickness of chimney shell, in.
    \item \( t_s \) = Thickness of air space or insulation, in.
    \item \( t_b \) = Thickness of lining, in.
    \item \( T \) = Maximum temperature of gas inside chimney, deg F.
\end{itemize}
$T_o=$ Minimum temperature of outside air surrounding chimney, deg F.
$C_c = 12 \text{ (Btu·in.)/(h·ft²·°F)}$ of thickness/h/°F difference in temperature; fo concrete;
$C_s =$ to be obtained from the manufacturer of the materials used;
$C_b =$ to be obtained from the manufacturer of the lining materials used;
$K_i =$ to be determined from curves in Fig.4;
$K_o =$ 12 Btu/(ft²·h·°F);
$K_r =$ Ti/120; and
$K_s =$ Ti/150.

d_{bi} =$ Inside diameter of lining, ft.
d_{bo} = Mean diameter of lining, ft.
d_s = Mean diameter of space between lining and shell, ft.
d_ci = Inside diameter of chimney shell, ft.
d_c = Mean diameter of chimney shell, ft.
d_co = Outside diameter of chimney shell, ft.

The value of $rq = 0.5$ shall apply only where the distance between
the lining and the chimney shell is not less than 4 in. Throughout
the entire height of the lining and air inlet and outlet openings are
provided at the bottom and top of the chimney shell. The area of the
inlet and outlet openings, in square feet, shall numerically equal
two-thirds of the inside diameter in feet of the chimney shell at the
top of the lining. Local obstructions in the air space between the
lining and the chimney shell shall not restrict the area of the air
space at any horizontal section to be less than that specified for air
inlet or outlet.

5.1.2 The research data available to establish the coefficients of
heat transfer through the chimney lining and shell, especially as
they concern the heat transfer from gases to the surfaces and
through ventilated air spaces between lining and shell, are
somewhat meager. Unless complete heat balance studies are
made for the particular chimney, it is permissible to use constants
as determined or stated in this standard.

- 125 -
5.1.3 The maximum stress in the vertical steel, $f_{STV}$, in psi, occurring at the outside face of the chimney shell due to temperature shall be computed by Eq. (20).

$$f_{STV} = \alpha_t e \times (\gamma_2 - c) \times T_x \times E_s \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ll
5.2.2 The maximum stress in psi in the outside circumferential reinforcement \( f_{\text{STC}} \) due to temperature shall be computed by Eq. (23).

\[
f_{\text{STC}} = \alpha \text{te} \times (\gamma^2 - c') \times T_x \times E_s \quad \ldots \ldots \text{(23)}
\]

5.3 Conversion of U.S. Customary Units to SI Units:

- 1 in. = 25.4 mm
- 1 ft = 0.304 8 m
- 1 psi = 0.006 895 N/mm\(^2\)
- 1 kip = 4.448 222 kN

\[
F^o = (C^o \times 9/5) + 32
\]

6. Field measurements:

This study was stimulated by the availability of field data taken from al-Dora chimney in Baghdad, the temperatures of air and concrete shell were taken in summer and winter in 1999, to provide a real thermal load case for any chimney in Baghdad and to make a comparison between the thermal load case in summer and winter. Any other important information was taken from control office in al-Dora power plant.

Table (1)

<table>
<thead>
<tr>
<th>Date</th>
<th>Air Temp.</th>
<th>Afternoon concrete temp. at each station, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-9</td>
<td>3-4 P.M.</td>
<td>Statio n A @315 St. B @0° St. C @45° St. D @90° St. E @135° St. F @180° St. G @225° St. H @270° &amp;Tm</td>
</tr>
<tr>
<td>14-9</td>
<td>29.7 5</td>
<td>40</td>
</tr>
<tr>
<td>15-9</td>
<td>28.7 5</td>
<td>39</td>
</tr>
<tr>
<td>16-9</td>
<td>26 5</td>
<td>35.7 5</td>
</tr>
<tr>
<td>Averag e</td>
<td>28.1 7</td>
<td>38.2 5</td>
</tr>
<tr>
<td>&amp;Tm</td>
<td>0 8</td>
<td>10.0 8</td>
</tr>
</tbody>
</table>

where: &Tm=Change in temp. from Morning average of 28.17 °C

&T=Temp. of station B (@ 0°) – Temp. of station F(@ 180°)
Air and concrete temperatures measurements at al-Dora chimney, in centigrade degrees, at Dec.

<table>
<thead>
<tr>
<th>Date</th>
<th>Air Temp.</th>
<th>Afternoon concrete temp. at each station, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-9 A.M.</td>
<td>3-4 P.M.</td>
<td>St. A @ 315</td>
</tr>
<tr>
<td>28-12</td>
<td>12.7</td>
<td>20.7</td>
</tr>
<tr>
<td>29-12</td>
<td>12.5</td>
<td>20</td>
</tr>
<tr>
<td>30-12</td>
<td>13</td>
<td>21.5</td>
</tr>
<tr>
<td>Average</td>
<td>12.7</td>
<td>20.7</td>
</tr>
<tr>
<td>&amp;Tm</td>
<td>0</td>
<td>8</td>
</tr>
</tbody>
</table>

where: &Tm=Change in temp. From Morning average of 12.75° C  
&T=Temp. Of station B (0°) – Temp. Of station F (180°)

6.1 Distribution of temperatures in chimney:

Using the equations for thermal stresses of ACI 307 08, the distribution of temperatures has been calculated as shown below:

\[ T_x = T_3 - T_4 = \frac{t \, dbi}{Cc \, dc} \left( \frac{T_i - T_0}{r_q \, K_i} + \frac{t \, dbi}{r_q \, K_i} + \frac{t \, dbi}{r_q \, K_i} + \frac{r_s \, ds}{Cc \, dc} + \frac{K_o \, dc}{Ko \, dc} \right) \]  

\[ \ldots \ldots (24) \]
Uniform temp. increase = $T_m - T_b$
Temp. gradient = $T_3 - T_4$

**Fig. 5** Distribution of temperatures in chimney

All temperature distribution have been calculated according to ACI 307 08, where:
- $T=170^\circ\text{C}$ for ordinary case = $338^\circ\text{F}$
- $=598^\circ\text{C}$ for ordinary case = $1100^\circ\text{F}$
- $T_o$ = temp. of air at each month = 0.5, 10, ……,
- $T = 225\text{ mm}=8.858\text{ in}$, $C_c=12\text{ Btu/ft}^2\text{ in.hr.F}$, $C_b=6$, $d_c=21.572\text{ ft}=6.6\text{ m}$, $r_o = 0.5$,
- $k_1 =7.58$, $d_b=12.008\text{ ft}=3.66\text{ m}$, $t_b=4.724\text{ in}=120\text{ mm}$, $d_b=11.811\text{ ft}=3.6\text{ m}$, $k_b=2.25$, $d_s=16.89\text{ ft}=5.15\text{ m}$, $k_o=12$, $d_{co}=22.31\text{ ft}=6.8\text{ m}$.

**Table (3)**

Distribution of temp. in $\text{\circ}C$ through chimney shell and lining in al-Dora chimney, for Ordinary case, where $T=170\text{ ^\circ}C$.

<table>
<thead>
<tr>
<th>$T_o$</th>
<th>$T_x$</th>
<th>$T_m$</th>
<th>$T_4$</th>
<th>$T_3$</th>
<th>$T_2$</th>
<th>$T_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>27.5</td>
<td>16.5</td>
<td>3</td>
<td>30</td>
<td>50</td>
<td>154</td>
</tr>
<tr>
<td>5</td>
<td>26</td>
<td>21</td>
<td>8</td>
<td>34</td>
<td>53.6</td>
<td>154.3</td>
</tr>
<tr>
<td>10</td>
<td>25.4</td>
<td>25.7</td>
<td>13</td>
<td>38.4</td>
<td>57.2</td>
<td>154.7</td>
</tr>
<tr>
<td>15</td>
<td>24.6</td>
<td>30.3</td>
<td>18</td>
<td>42.6</td>
<td>60.8</td>
<td>155</td>
</tr>
<tr>
<td>20</td>
<td>23.8</td>
<td>34.9</td>
<td>23</td>
<td>46.8</td>
<td>64.4</td>
<td>155.3</td>
</tr>
<tr>
<td>25</td>
<td>23</td>
<td>39.5</td>
<td>28</td>
<td>51</td>
<td>68</td>
<td>155.7</td>
</tr>
<tr>
<td>30</td>
<td>22.2</td>
<td>44.1</td>
<td>33</td>
<td>55.2</td>
<td>71.6</td>
<td>156</td>
</tr>
<tr>
<td>35</td>
<td>21.4</td>
<td>48.7</td>
<td>38</td>
<td>59.4</td>
<td>75.2</td>
<td>156.3</td>
</tr>
<tr>
<td>40</td>
<td>20.6</td>
<td>53.3</td>
<td>43</td>
<td>63.6</td>
<td>78.8</td>
<td>156.7</td>
</tr>
<tr>
<td>45</td>
<td>20</td>
<td>58</td>
<td>48</td>
<td>68</td>
<td>82.4</td>
<td>157</td>
</tr>
<tr>
<td>50</td>
<td>18</td>
<td>62.5</td>
<td>53</td>
<td>72</td>
<td>86</td>
<td>157.3</td>
</tr>
<tr>
<td>55</td>
<td>18.2</td>
<td>67.1</td>
<td>58</td>
<td>76.2</td>
<td>89.6</td>
<td>157.7</td>
</tr>
<tr>
<td>60</td>
<td>17.4</td>
<td>71.7</td>
<td>63</td>
<td>80.4</td>
<td>93</td>
<td>158</td>
</tr>
</tbody>
</table>

- 129 -
Table (4)
Distribution of temp. in °C through chimney shell and lining in Al-Dora chimney, for Emergency case, where T=598 °C.

<table>
<thead>
<tr>
<th>To</th>
<th>Tx</th>
<th>Tm</th>
<th>T4</th>
<th>T3</th>
<th>T2</th>
<th>T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>94</td>
<td>57</td>
<td>10</td>
<td>104</td>
<td>112</td>
<td>151</td>
</tr>
<tr>
<td>5</td>
<td>93.25</td>
<td>61</td>
<td>15</td>
<td>108</td>
<td>121</td>
<td>184</td>
</tr>
<tr>
<td>10</td>
<td>92.5</td>
<td>65</td>
<td>20</td>
<td>112</td>
<td>130</td>
<td>217</td>
</tr>
<tr>
<td>15</td>
<td>91.75</td>
<td>69</td>
<td>25</td>
<td>116</td>
<td>139</td>
<td>250</td>
</tr>
<tr>
<td>20</td>
<td>91</td>
<td>73</td>
<td>30</td>
<td>121</td>
<td>148</td>
<td>283</td>
</tr>
<tr>
<td>25</td>
<td>90.25</td>
<td>77</td>
<td>35</td>
<td>125</td>
<td>157</td>
<td>316</td>
</tr>
<tr>
<td>30</td>
<td>89.5</td>
<td>81</td>
<td>40</td>
<td>129</td>
<td>166</td>
<td>349</td>
</tr>
<tr>
<td>35</td>
<td>88.75</td>
<td>85</td>
<td>45</td>
<td>133</td>
<td>175</td>
<td>382</td>
</tr>
<tr>
<td>40</td>
<td>88</td>
<td>89</td>
<td>50</td>
<td>137</td>
<td>184</td>
<td>415</td>
</tr>
<tr>
<td>45</td>
<td>87.25</td>
<td>93</td>
<td>55</td>
<td>141</td>
<td>193</td>
<td>448</td>
</tr>
<tr>
<td>50</td>
<td>86.5</td>
<td>97</td>
<td>60</td>
<td>146</td>
<td>202</td>
<td>480</td>
</tr>
<tr>
<td>55</td>
<td>85.75</td>
<td>101</td>
<td>65</td>
<td>150</td>
<td>211</td>
<td>513</td>
</tr>
<tr>
<td>60</td>
<td>85</td>
<td>104</td>
<td>70</td>
<td>155</td>
<td>220</td>
<td>543</td>
</tr>
</tbody>
</table>

7. Comparison of construction materials studies
Chimneys of different construction materials with same dimensions are studied for thermal response analysis. These chimneys are linearly tapered from base up to the top.

The chimneys are concrete, steel, stainless steel, and aluminum. The dimensions of all chimneys are:
Height =45 m, Base diameter =3.2m, top diameter =2 m
Thickness of shell =14 mm (accept for concrete chimney =15 cm)

Table (5)

<table>
<thead>
<tr>
<th>Name</th>
<th>E kN/mm²</th>
<th>Poisson’s Ratio</th>
<th>Density kg/m³</th>
<th>Alpha @°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEEL</td>
<td>205.000</td>
<td>300E-3</td>
<td>7833.413</td>
<td>12E-6</td>
</tr>
<tr>
<td>STAINLESSSTEEL</td>
<td>197.930</td>
<td>300E-3</td>
<td>7833.413</td>
<td>18E-6</td>
</tr>
<tr>
<td>ALUMINUM</td>
<td>68.948</td>
<td>330E-3</td>
<td>2712.631</td>
<td>23E-6</td>
</tr>
<tr>
<td>CONCRETE</td>
<td>21.718</td>
<td>170E-3</td>
<td>2402.615</td>
<td>10E-6</td>
</tr>
</tbody>
</table>

In this study STAAD.Pro V8i software with plate finite element was used. The STAAD plate finite element is based on hybrid finite element formulations. A complete quadratic stress distribution is assumed. For plane stress action, the assumed stress distribution is as follows:
The following quadratic stress distribution is assumed for plate bending action:

- $S_{QX}, S_{QY} =$ Shear stresses (Force/unit len./thk.)
- $S_X, S_Y, S_{XY} =$ Membrane stresses (Force/unit len./thk)
- $M_X, M_Y, M_{XY} =$ Moments per unit width (Force x Length/length)

*(For $M_x$, the unit width is a unit distance parallel to the local Y axis, For $M_y$, the unit width is a unit distance parallel to the local X axis. $M_x$ and $M_y$ cause bending, while $M_{xy}$ causes the element to twist out-of-plane.)*
8. Results of analyses

![Finite Element Idealization of chimney](image)

**Fig. (8)** Finite Element Idealization of chimney

8.1 Effect of material of shell:

![Radial displacement due to thermal stresses, for the four chimneys.](image)

**Fig. (9)** Radial displacement due to thermal stresses, for the four chimneys.
Fig. (10) Vertical displacement due to thermal stresses, for the four chimneys.

Fig. (11) $M_x$ due to thermal stresses, for the four chimneys.
Fig. (12) $M_Y$ due to thermal stresses, for the four chimneys.

Fig. (13) $S_{QY}$ due to thermal stresses, for the four chimneys.
Fig. (14) $S_x$ due to thermal stresses, for the four chimneys.

Fig. (15) $S_y$ due to thermal stresses, for the four chimneys.

Table 6  (Reactions for the four chimneys.)

<table>
<thead>
<tr>
<th>Chimney type</th>
<th>Weight of shell (kN)</th>
<th>Radial force at base, (kN)</th>
<th>Vertical force at base, (kN)</th>
<th>Moment at base, (kN.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum chimney</td>
<td>133.41</td>
<td>734.507</td>
<td>16.693</td>
<td>146.393</td>
</tr>
<tr>
<td>Stainlesssteel chimney</td>
<td>385.255</td>
<td>1147.787</td>
<td>48.182</td>
<td>231.579</td>
</tr>
<tr>
<td>Steel chimney</td>
<td>385.255</td>
<td>1660.04</td>
<td>48.194</td>
<td>336.521</td>
</tr>
<tr>
<td>Concrete chimney</td>
<td>1266.031</td>
<td>1588.464</td>
<td>158.257</td>
<td>478.272</td>
</tr>
</tbody>
</table>
8.2 Effect of changing thickness of shell:

Two similar concrete chimneys with difference thicknesses (15 and 25 cm) were taken, the results were as shown below:

**Fig.(16)** $S_X$ due to thermal stresses, for the two chimneys.

**Fig.(17)** $M_Y$ due to thermal stresses, for the two chimneys.
Fig. (18) Radial disp. due to thermal stresses, for the two chimneys.

Fig. (19) Vertical disp. due to thermal stresses, for the two chimneys.

Table 7 (Reactions for the two chimneys.)

<table>
<thead>
<tr>
<th>Chimney type</th>
<th>Weight of shell (kN)</th>
<th>Radial force at base, (kN)</th>
<th>Vertical force at base, (kN)</th>
<th>Moment at base, (kN.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete chimney with t=15cm</td>
<td>1266.031</td>
<td>1588.464</td>
<td>158.257</td>
<td>478.272</td>
</tr>
<tr>
<td>Concrete chimney with t=25cm</td>
<td>2110</td>
<td>1634</td>
<td>264</td>
<td>606</td>
</tr>
</tbody>
</table>
8.3 Effect of lining on the chimney:
Two similar concrete chimneys were taken, the first with air space and brick lining(thickness=12cm) and the other without lining, so the last one will take a higher thermal load to a temperature about 550 °C which means that the value of modulus of elasticity and thermal expansion must changes, the results are as shown below:

![Graph 20](image)

**Fig.(20)** $M_y$ due to thermal stresses, for the two chimneys.

![Graph 21](image)

**Fig.(21)** Radial disp. due to thermal stresses, for the two chimneys.
Fig. (22) $S_X$ due to thermal stresses, for the two chimneys.

Fig. (23) Vertical disp. due to thermal stresses, for the two chimneys.

Table 8 (Reactions for the two chimneys.)

<table>
<thead>
<tr>
<th>Chimney type</th>
<th>Weight of shell (kN)</th>
<th>Radial force at base, (kN)</th>
<th>Vertical force at base, (kN)</th>
<th>Moment at base, (kN.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete chimney with $t=15$ cm</td>
<td>1266.031</td>
<td>1588.464</td>
<td>158.257</td>
<td>478.272</td>
</tr>
<tr>
<td>Concrete chimney with, $t=15$ cm, without lining</td>
<td>1266.031</td>
<td>6676</td>
<td>158.264</td>
<td>2048.7</td>
</tr>
</tbody>
</table>
9. Conclusions:

1- The analysis of the four chimneys give a result of vertical and radial displacements with descending sort (Aluminum, Stainless Steel, Steel, and concrete chimneys), this is because of the value of modulus of elasticity, density and thermal expansion coefficient.

2- Bending moments and shear stresses have similar values for the metal chimneys, but the concrete chimney has different values because of the difference in thickness and mechanical properties.

3- The four chimneys give results of membrane stresses ($S_x$ and $S_y$) with a descending sort (Stainless Steel, Steel, Aluminum, and concrete chimney).

<table>
<thead>
<tr>
<th>Chimney type</th>
<th>$S_x$ (N/mm$^2$)</th>
<th>$S_y$ (N/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>13.51</td>
<td>3.81</td>
</tr>
<tr>
<td>Steel chimney</td>
<td>9.51</td>
<td>3.41</td>
</tr>
<tr>
<td>Aluminum chimney</td>
<td>6.1</td>
<td>1.51</td>
</tr>
<tr>
<td>Concrete chimney</td>
<td>1.1</td>
<td>0.71</td>
</tr>
</tbody>
</table>

These values at level =6.75 m from the base of chimney

4- The four chimneys give results of reactions at the base with a descending sort (concrete, Steel, Stainless Steel, and Aluminum chimney), so the concrete chimney will need a larger footing.

5- The lining reduces the thermal stresses to the (25-50)%, by reducing heat which reaches the chimney shell, while increasing in the thickness of the shell has no effect on thermal stresses except at the shell base where the boundary conditions must be satisfied.

6- The thickness of the shell is proportional to the reactions at the base of the chimney and inversely proportional to the radial and vertical displacements.

7- Winter time is found to be more critical since it gives higher temperature difference.

8- The Uniform heating component is more effective on the bending moments, membrane stresses and vertical displacement than the second component (temperature gradient), while the rotations are not affected much by thermal loads.
References:


10- American Concrete Institute Committee 307, "Specification for the design and construction of reinforced concrete Chimneys" ( ACI 307 08), American Concrete Institute, Detroit, mich., 2008.

11- STAAD.Pro V8i,(Structural Analysis And Design) Software, Installation and User's manual.USA.
التحليلات الحرارية للمدخنات باستخدام طريقة العناصر المحدد

. بشار فصيل عبدالكريم

المستخلص

هذا البحث يعني بدراسة تأثير الاعمال الحرارية على المدخن حيث أن الاعمال الحرارية الماخوذة بنظر الاعتبار في هذا البحث بناء على القياسات النقطية الواقعة لتياب درجات الحرارة على مدخنة الدورة وبالتالي اعتبارها كبيانات وافية لدرجات الحرارة لأي مدخنة يتم انشاؤها في بغداد . وهذة التغييرات الحرارية تقسم إلى قسمين من حيث التأثير وهما:

1- التوسع المنتظم (Uniform heating)

2- التسخين المنتظم (Temperature gradient)

عبر سمك قشرة المدخنة نتيجة لمرور

تم إنجاز التحليلات الحرارية باستخدام أشتراطات المواصفة الأمريكية (08-307-08) والبحث المنتزه باستخدام STAAD.Pro-V8i وتعريف المنشأ باستخدام عنصر 3D - plate element

تم دراسة سلوك أربعة مدخنات مشابهة بالشكل والإبعاد ولكنها تختلف بمواد إنشاؤها(الخرسانية الحديدية الحديدية غير القابلة للصدأ والأنسيومي). وقد وجد بأن المدخنات المعدنية تعطي نتائج أعلى للازاحة الشعاعية والعمودية بينما بالنسبة لعزم الانحناء (bending moments) والإجهادات الغشائية (Membrane Stresses) فهى قليلة وبالتالي لا داعى لتكبير سمك قشرة المدخنة بهدف تقليل الإجهادات الحرارية. وانما الانتقاء بطريقة التبطن والتهوية لأنها الأكثر تأثيراً بتقليل الإجهادات الحرارية.

أخيراً وجد أن تركيز الحمل الحراري الأولي (Uniform heating) وان نسبته يكون حسب الظروض والازاحة العمودية. وان الدوران لا يؤثر كثيراً بالإعمال الحرارية فصل الشتاء هو الأكثر خطورة لأنه يعطي الانحدار الحراري الأخبار في قشرة المدخنة.

كلية المنصور الجامعة