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Research paper

Study the Effect of Heat Transfer Coefficient and Thermal Conductivity on Cracked Pipes Carrying Pressurized Fluid

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Abstract

The cylindrical pipes carrying pressurized fluid at high-temperature environment have many engineering applications such as cooling systems of the power plant. In this paper, the effect of the presence of crack and the thermal stress distribution of the pipe has been studied numerically. The “mode I” type of crack has been considered for the study. The stress distributions, stress intensity factor and J-integral calculations were considered. The results have been validated with an available analytical solution for a pristine cylinder. Special attention and mesh scheme has been used around the crack to obtain the accurate stress distributions. The temperature and stress variations for pressurized fluids with different heat transfer coefficients and pipe’s conductivity were studied. It was found that the convection heat transfer coefficient has an accountable effect on the stress distributions. The stresses increased by 5% for different heat transfer coefficient without cracks. Moreover, the stress intensity factor and the J-integrals were calculated for different crack length ratios. The stress intensity factor increased by 14% when the crack length ratio is 0.7. In addition, the effect of pipe thermal conductivity has been studied. It was found that the thermal conductivity influences the stress distributions, stress intensity factor and J-integral values. The stresses decreased by 15% with increasing the thermal conductivity without cracks, the J-integral and the stress intensity factor decreases as the thermal conductivity of the pipe increases for different crack length ratios.

Keywords: *Crack Length, Thermal Loading, Stress Distribution, J-Integral, Heat Transfer Coefficient, Thermal Conductivity.*

1. Introduction

Investigation the influence of thermal loading on stress distributions and J-integral values in cracked pressurized pipes is importantstudybecause of many applications in engineering constructions in cooling processes such as power generation plant and nuclear power plant. Thermal loadings have a tremendous effect on stress analysis, stress intensity factor and J-integral values for different crack lengths.The value of J-integral represents a method to obtain the strain energy release rate per unit surface area offracture [1].A numerical method to compute the stress intensity factor for longitudinal semi-elliptical surface cracks in a pipe under thermal loading was used [2]. The time dependence of the stress intensity factor shows a maximum for short times, with increasing crack depth. Then, after passing this maximum, the values decrease slowly until the stationary values for long times are reached. Analyzing the inclined cracks in thermally stressed planar structures was studied numerically [3]. A crack inclined at an angle 22.5 to horizontal, embedded in a rectangular plate, where a thermal load at the crack surface and the outer boundary was applied. Crack tip element that accurately models the behavior of displacement, temperature fields, the singularity of traction, and flux field is used for the accurate evaluation of stress intensity factor. They concluded that the mode I stress intensity factor increase monotonically to the steady-state value and the mode II stress intensity factor increase to a peak after a short time before it decreases gradually to the steady-state value. The transient thermal stress in edge cracked plate for the sudden surface heating where the plate is insulated on one face and heated on the other [4].
The temperature distribution needed to obtain these stresses determined using Laplace transform, and thermal stress obtained using force and momentum equilibrium equations. Finite element method and weighted function method to the computation of the stress intensity factor for a cracked vessel and pipe subjected to thermal loading were studied [5]. They concluded that the stress intensity factor influenced by the heat convection at the crack face, and affected by Biot numbers, where the large Biot number showed a large stress intensity factor. Thermal stress of optically accessible quartz cylinder which can be operated without breaking utilized using finite element analysis [6]. Steady state heat transfer and stress analysis were accomplished using ABAQUS package, where heat transfer analysis was conduct first. Subsequently, the heat transfer result and combustion pressure were used to perform the stress analysis which is capable of causing a sudden quartz cylinder breaking during fired operation. Improving current quartz engine which forced convection of outside cylinder is a very effective method to decrease the maximum stress level. Moreover, the natural convection case engine can work with asafety factor of about 2. Quartz cylinder under intensive forced convection can be operated with a safety factor of about 2.7 and without concern about the maximum temperature limit.

Derivation of a new algorithm was discussed [7] for the calculation of J-Integral for both linear elastic and elastic-plastic fracture mechanic using finite element and boundary element methods with different types of loading. Some case studies with elastic, thermal elastic and elastoplastic conditions, and with one and two modes of fracture. The J-Integral is very efficient and advantageous for both linear elastic and elastic-plastic fracture mechanic. A numerical analysis to derive theexpression of the J-integral for center cracked plate under thermal and mechanical loading conditions was developed [8]. Two-dimensional finite element analysis and quadratic isoparametric element were used for mode I loading. The increase of specific heat, thermal conductivity, thermal diffusivity, young modulus, the temperature difference between the crack side edge and crack length, increase the rate of J-integral under mode I thermal shock loading.

In [9], they discussed two-dimensional finite element analysis where the J- integral within the plastic zone was characterized for different strain hardening materials [9]. The nonlinear material behavior was model using the incremental plasticity theory. There are two cases for J-Integral: dependent and independent, the first would be happen if the selected integration contour cannot fully enclose the plastic zone, otherwise it is independent. The effect of the biaxial stress on the J-integral which containing a through thickness crack and subjected to biaxial stress was studied by [10]. They developed program including three and two-dimensional incremental theory elastic-plastic finite element. It is clearly noticed that the J-integral path independence would be significantly changed when the load perpendicular to crack length direction is greater than 80% of the ultimate specimen load (or plastic limit load). Also,

It is showed that the J-integral values will differ significantly from other J-Integral values under biaxial and uniaxial respectively. These values would be changed when the load perpendicular to the crack length direction is greater than 80% of the ultimate specimen load. Declining the length of yielding plateau will reduce the difference of the J-integral values between the biaxial stressing condition and uniaxial stressing condition.

In this work, thermal stress analyses, J-Integral calculations, and stress intensity factor were investigated numerically for pressurized pipes and cracked pressurized pipes. The influence for convection heat transfer coefficient on stress distributions and J-integral values was studied for pipes with no cracks and with longitudinal crack. In addition, the effect of the pipe's thermal conductivity on thermal stresses and J-Integral was discussed.

2. Theoretical Modeling

In order to investigate the effect of thermal loadings on pressurized pipes and cracked pressurized pipes, a numerical model was developed using the finite element method. The solution of the two-dimension analyzing of displacement and stress distribution on pipes with thermal loadings were solved using Fortran 90 language. The program consists of calculating the J-integral and stress intensity factor values under the effect of thermal loadings. The schematic solver program was explained in

Fig. 1. Due to the symmetry conditions, a quarter of pipe was used in this study.
The displacement vector $\underline{u}$ at any point (x,y) can be expressed as follows [7]:

$$\underline{U}(x,y) = \sum_{i=1}^{n} U_i N_i(x,y) \quad (1)$$

The element stiffness matrix for two-dimensional elasticity problems is as follows [7]:

$$\underline{K}_{(e)} = \int_y \int_x \underline{B}^t \underline{D} \underline{B}\, t\, dx\, dy \quad (2)$$

Where $\underline{B}$ is the matrix which relates the strain vector to the nodal displacement vector and D is the stress-strain matrix that is given for plain stress conditions [7]:

$$\underline{B} = \begin{bmatrix} \cdots \frac{\partial N_i}{\partial x} & 0 \cdots \\ \cdots 0 & \frac{\partial N_i}{\partial y} \cdots \\ \cdots \frac{\partial N_i}{\partial y} & \frac{\partial N_i}{\partial x} \cdots \end{bmatrix} \quad (3)$$

$$\underline{D} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix} \quad (4)$$

Where, E = Young's modulus of elasticity, υ = Poisson's ratio. Then, the nodal stiffness and nodal load are integrated to obtain the net stiffness and the net load at the specified node.

$$\underline{K} = \sum_{e=1}^{n_e} \underline{K}_{(e)} \quad (5)$$

$$\underline{F} = \sum_{e=1}^{n_e} \underline{F}_e \quad (6)$$

The overall system of the equations of the domain is [7]:

$$\underline{K} \cdot \underline{U} = \underline{F} \quad (7)$$

Once the displacements have been determined, the element strains and stresses can be calculated using stress-strain relations.

$$\varepsilon = B\, U \quad (8)$$

and

$$\sigma = D\varepsilon \tag{9}$$

Hence, it can be shown that:

$$\sigma = D\ B\ U \tag{10}$$

The overall system of equations for the domain can be written as follows:
K. U = F
Where U is the global displacement vector.

2.1 Boundary Conditions

In order to solve system ofequations, the following boundary conditions are implemented:
1-The pressure loading has a constant value of 10 Mpa.
2- The displacement values are zero at the edges of the pipe due to symmetry conditions.
3- The ambient temperature T_∞ is 27 ℃ which is outside environment temperature.
2- The heat transfer coefficient inside the pipe is 5000 $\frac{w}{m^2.k}$.

2.2 Thermal Loadings

The temperature distribution T at any point (x,y) can be expressed as follows[11]

$$\mathbf{T}\,(x,y) = \sum_{i=1}^{n} T_i N_i(x,y) \tag{11}$$

The force element matrix as follows:

$$\underline{F}_e = \int_S q\, N^t\, ds + \int_s h\, T_\infty N^t\, ds \tag{12}$$

$\underline{F}_e$is the element stiffness force, q is the heat flux on surface and$T_\infty$is the fluid's temperature.

The nodal stiffness and nodal load for each of the element node are integrated to obtain the net stiffness and the net load at the specified node.

$$\underline{K} = \sum_{e=1}^{ne} \underline{K}_e \tag{13}$$

and the global force vector as:

$$\underline{F} = \sum_{e=1}^{ne} \underline{F}_e \tag{14}$$

Where the element stiffness matrix becomes:

$$\underline{K}_e = \int_y \int_x \underline{B}^t \underline{DB}\, t\, dxdy \tag{15}$$

The $\underline{D}$ matrix can be expressed for two-dimensional heat transfer problem as [11]:

$$\underline{D} = \begin{bmatrix} K_x & 0 \\ 0 & K_y \end{bmatrix} \tag{16}$$

The overall system for temperature is

$$\underline{K}.\ \underline{T} = \underline{F} \tag{17}$$

Once the temperature distributions have been determined, the element thermal strains and stresses can be calculated using stress-strain relations. The initial thermal strain can be expressed as follows[11].

$$\varepsilon_x^\circ = \varepsilon_y^\circ = \alpha` T \tag{18}$$

$$\sigma_x{}^\circ = \sigma_y{}^\circ = D\varepsilon_x^\circ \tag{19}$$

2.3 J- Integral for Thermal Loading

The strain energy term in the J-integral equation may be written as follows [11]:

$$J = \iint_\Gamma W\, dy - \iint_\Omega \sigma^t \frac{d\varepsilon}{dt} dxdy \tag{20}$$

Where ε represents the total strain vector. For the elastic stress-strain relationship. In case of thermal loading, the J-integral expression for thermal loading only as:

$$J = \iint_\Omega \sigma^t \frac{\partial \varepsilon^\circ}{\partial x} dxdy - \iint_\Gamma T^t \frac{\partial U}{\partial x} ds \tag{21}$$

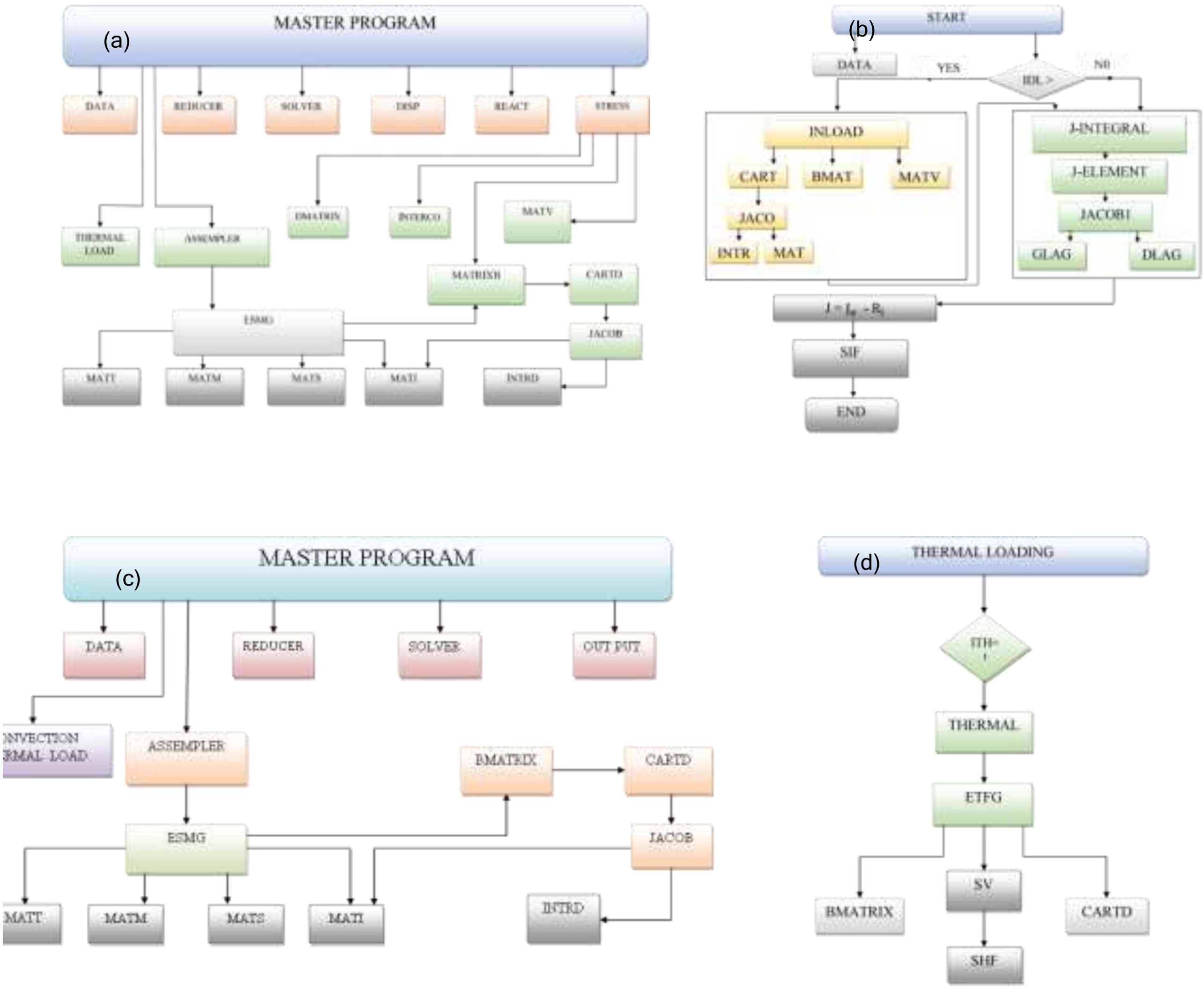


Fig. 1: The schematic solver program (a) the stress distribution (b) J- integral program calculation (c) temperature distribution (d) thermal loading effect.

3. Results and Discussion

Study the influence of thermal loading (conduction and convection) on stress distribution and the J-integral calculations for pressurized pipes and cracked pressurized pipes under different crack lengths is discussed. The pipes were pressurized by the internal pressure of 10 Mpa. The ambient temperature is 27 °C, and the heat transfer coefficient is 5000 $\frac{w}{m^2.k}$. The numerical model was analyzed using finite element method and programmed using Fortran 90. The validation of the numerical results is compared with analytical solution [11] for a pipe that subjected to internal pressure loading only (case 1).Then, the numerical analysis was performed on the pipes to study the effect of the heat transfer coefficient during convection (case 2) and the influence of the material's thermal conductivity (case 3). The parameters for case 1, case 2, and case 3were listed in Table 1. The evaluation of J-Integral for various cases with a different type of crack lengths and thermal-structural boundary conditions are discussed. The geometry of the cylinder and the schematic mesh are shown in **Fig. 2**.Due to symmetry,a quarter of the cylinder has been used for mesh and solution using 80 quadrilateral 8-nodes standard element and plain strain conditions for all case studies.The displacements, the radial and tangential stresses of the cylinder are shown in **Fig. 3** and the results were compared with analytical solution [11].

Table 1: Parameters of case studies

	R_i (mm)	R_o (mm)	Loading
Case 1	70	110	α
Case 2	1.9	2.1	α+β
Case 3	1.9	2.1	α+β

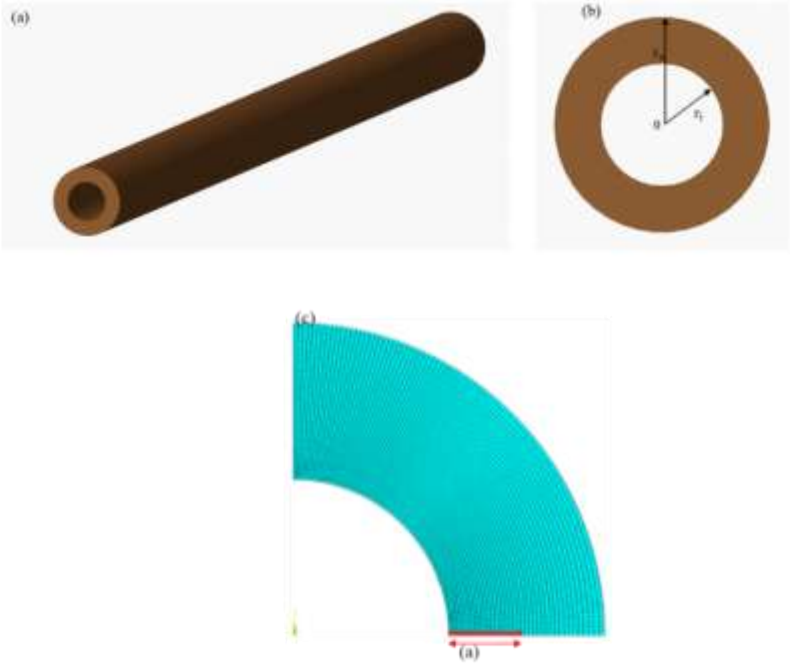
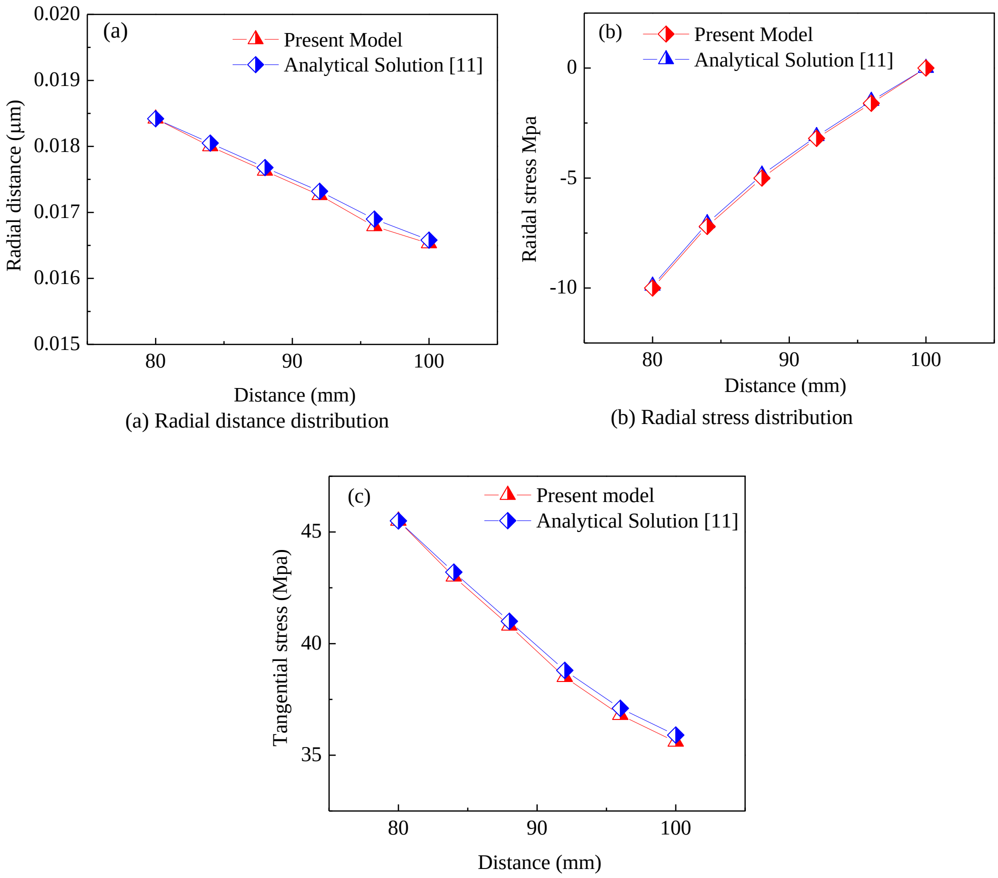


Fig. 2: (a) a cylindrical pipe (b) the cross-section of the pipe, (c) the meshed of quarter section of the pipe.



(a) Radial distance distribution

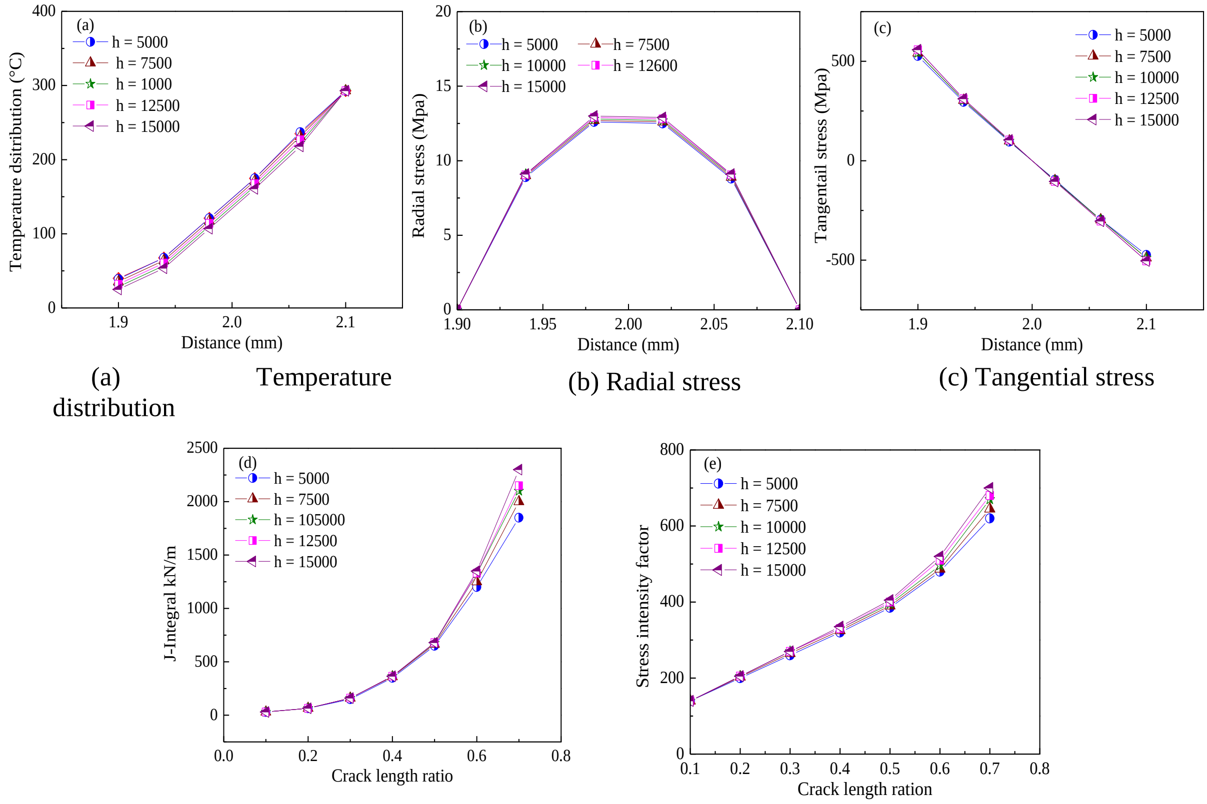
(b) Radial stress distribution

(c) Tangential stress distribution

Fig. 3: (a) The displacements (b) the radial stress (b) tangential stress through the cylinder.

3.1 Effect of Heat Transfer Coefficient

The stress analysis of a pressurized pipe which exposed to thermal convection loading and internal pressure are discussed. The thermal loading is applied on the inner surface where the ambient temperature T_{∞}= 27C$^{\circ}$and the heat transfer coefficient ranging between (5000-15000 W/m^2.k) while the outer surface is maintained at constant temperature conditions. The temperatures, the radial and, tangential stresses distributions are shown in **Error! Reference source not found.** (a-c).The temperature difference increases with increase in the convection heat transfer coefficient because of the proportional relation between the convection heat transfer and the temperature difference according to Newton's law of cooling. Then, the thermal stresses increase with increase t in he heat transfer coefficient because of the decrease in the temperature differences. The radial stresses increased by 5% when the heat transfer coefficient is 15000 W/m^2.k.Thepressurized pipe that subjected to radial crack and same boundary conditions is analyzed. The stresses ahead of the crack tip reached a critical magnitude and the tangential stress is higher than radial stress which lead to open the crack. The radial stress has less effect than tangential stress around the crack region. The J-integral values and stress intensity factor for different crack ratios and heat transfer coefficient are shown in **Error! Reference source not found.** (d-e). The J-integral and stress intensity factor increase with increase the crack lengths and heat transfer coefficient because of increase the thermal stresses due to the increase of temperature differences. The J-integral and stress intensity factor values increased by 14 % when the heat transfer coefficient is 15000 W/m^2.k.



(a) Temperature distribution (b) Radial stress (c) Tangential stress

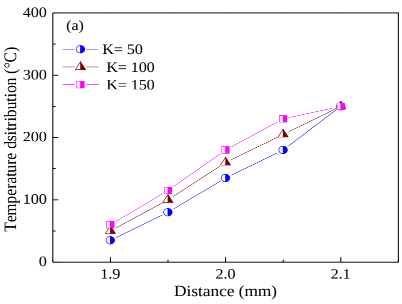
(d) J-integral (e) Stress intensity factor

Fig. 4: The effect of heat transfer coefficient W/m^2.k(a) The temperatures distributions (b) radial variation of the radial stress (c) tangential stresses (d) The J-integral for different crack ratios (e) The stress intensity factor at different crack length ratios.

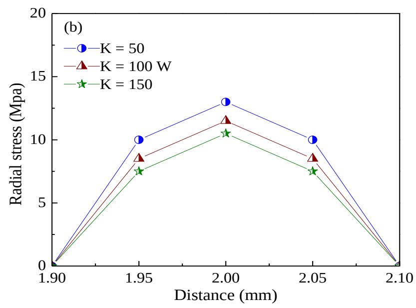
3.2 Effect of Thermal Conductivity

In this case, the effect of pipe's thermal conductivity on thermal stresses, J-integral and stress intensity factor values is discussed. The pipe is exposed to internal pressure and thermal convection loading. The inner surface is exposed to convection thermal loading where the ambient temperature $T_\infty$is 27C$^\circ$and the heat transfer coefficient is maintained constant at (5000$\frac{\mathrm{w}}{\mathrm{m^2.k}}$) while the pipe's thermal conductivity changed from (50-150) $\frac{\mathrm{w}}{\mathrm{m.k}}$.The temperature distributions, the radial stresses and tangential stresses are shown in **F** (a-c). The temperature difference decreases with increasing the thermal conductivity at the one surface due to the inverse relationship between the thermal conductivity and the temperature difference according to the Fourier's law. The radial and tangential stresses decreased with increase the thermal conductivity because of the decrease in temperature difference (ΔT) between the outer and inner surfaces

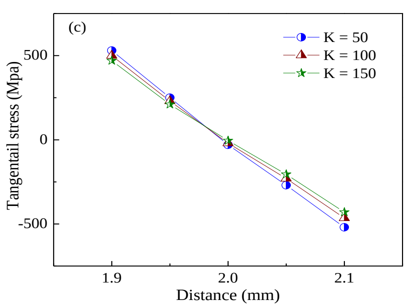
of the cylinder according to Fourier's law. The radial stresses decreased by 15% when the thermal conductivity is 150 $\frac{\mathrm{w}}{\mathrm{m^2.k}}$ compared the radial stress when the thermal conductivity is 50 $\frac{\mathrm{w}}{\mathrm{m^2.k}}$. The effect of pipe's thermal conductivity on the pressurized pipe with radial crack and same boundary conditions is studied. The inner surface of the pipe which has radial crack is exposed to convection thermal loading while the pipe's thermal conductivity changed. The, J-integral and stress intensity factor values for different crack ratios and pipe's thermal conductivity are shown in F (d-e).The J-integral and stress intensity factor decrease with increase the crack lengths and pipe's thermal conductivity because of decrease the thermal stresses due to the decrease of temperature differences according to the Fourier's law. The J-integral and stress intensity factor values decrease by 20 % when the thermal conductivity is 150 W/m.k because of the decrease in the thermal stresses.



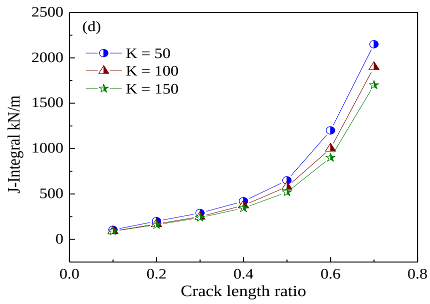
(a)Temperature distribution



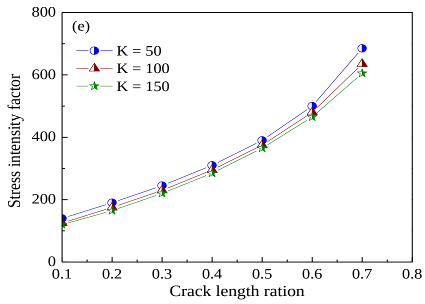
(b) Radial stress



(c) Tangential stress



(d) J-integral



(e) Stress intensity factor

Fig. 5: (a) The effect of thermal conductivity W/m. K (a) The temperature distributions (b) The radial stresses (c) Tangential stresses (d) The J-integral for different crack ratios (e) The stress intensity factor at different crack length ratio

4. Conclusions

In this paper, the thermal loading effect on stress analysis and J- integral calculations of pressurized pipes and cracked pressurized pipes is discussed. The influence of convection heat transfer coefficient and material's thermal conductivity were investigated. The heat transfer coefficient affects the J-integral values and stress distributions of pipes with and without cracks. The thermal stresses increase with increase the convection heat transfer by 5 %. Also, the J-integral increase when heat transfer coefficient increasing for different crack lengths. The J- integral values increased by 14% when the crack length is 0.7.In addition, the pipe's thermal conductivity influences the stress distributions and the J-Integral values for various crack's lengths. The thermal stress decreases with increasing the pipe's thermal conductivity and the J- integral value decrease by 15 % with increase the pipe's thermal conductivity for each crack length.

Nomenclature

E Modulus of elasticity Mpa
JJ-Integral N/m
Ni shape function
N Number of nodes
T_∞ Temperature of the surrounding °C
t Thickness of structure m
T Temperature difference°C
U Strain energy
u, v Displacements in the x and y-directions
R_i Inner radius m
R_o Outer radius m
α Coefficient of thermal expansion 1/K
q Heat flux on the surfaceW/m^2
k Thermal conductivity W/m. K
h Heat transfer coefficient W/m^2. K

Greeks symbols

ε Normal strain
ν Poisson's ratio
σNormal stress
i node's number

Matrices and Vectors

<u>B</u>Strain - Displacement Matrix

D Material Properties Matrix
FForce vector
TTemperature vector
UDisplacement vector
ε Strain vector
σStress vector
α Pressure loading
β Thermal loading

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