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การวิเคราะห์การถ่ายเทความร้อนและความเค้น ภายในท่อที่มีของเหลวร้อนไหลผ่าน

ANALYSIS OF HEAT TRANSFER AND STRESS IN THE PIPE WITH HOT FLUID FLOWING THROUGH

<u>อภิสรา เจริญศรี</u>*, พิพัฒน์ พิเชษฐ์พงษ์ และ เชาวน์ รอดทองคำ

<u>Apisara Charoensri</u>*, Pipat Pichestapong, Chouvana Rodthongkom

Chemistry and Material Science Research Program, Office of Atoms for Peace, Bangkok 10800, Thailand
Phone 0-25795230 ext. 421, Fax. 0-25613013; e-mail address: apisara@oaep.go.th

บทคัดย่อ: ณ บริเวณพื้นที่ที่มีของเหลวซึ่งมีอุณหภูมิสูงและอุณหภูมิต่ำไหลผ่านสัมผัสผิวหน้าของวัสดุ การเปลี่ยนแปลงอุณหภูมิของของเหลวจะทำให้ผนังของวัสดุเกิดความล้าซึ่งเป็นผลเนื่องมาจากความร้อน ปรากฏการณ์นี้เรียกว่า thermal striping สำหรับการออกแบบระบบท่อซึ่งภายในมีการไหลของของเหลวที่มีอุณหภูมิสูงและต่ำ สิ่งสำคัญที่จะต้องคำนึงถึง คือ ความเค้นทางความร้อน (thermal stress) ของวัสดุ อันเนื่องมาจากการพาความร้อน (heat convection) ของของไหล ในการศึกษานี้ เป็นการวิเคราะห์หาค่าความเค้นทางความร้อนจากการเปลี่ยนแปลงอุณหภูมิของของเหลว ที่มีผลต่อพื้นที่ผิวของวัสดุนั้น โดยสามารถประเมินค่าความสัมพันธ์ของการเปลี่ยนแปลงอุณหภูมิของของเหลวและการถ่ายเทความร้อนในวัสดุ ปัญหาในกระบวนการนี้เกี่ยวกับอุณหภูมิของของไหลและความถี่ของการเปลี่ยนแปลงอุณหภูมิของของไหล ซึ่งมีผลต่อพื้นที่ผิวของวัสดุนั้นและสัมพันธ์กับการถ่ายเทความร้อนของของไหลกับวัสดุ การศึกษากระทำโดยวิเคราะห์ความเค้นโดยใช้โปรแกรมคอมพิวเตอร์ "FINAS" ซึ่งใช้หลักการของวิธีไฟไนต์เอลิเมนต์ และเปรียบเทียบผลกับการคำนวณทางทฤษฎี โดยกำหนดขอบเขตการศึกษาว่าภายในท่อเกิด การพาความร้อนของของเหลวไปยังพื้นที่ผิวด้านในของวัสดุ ส่วนพื้นที่ผิวด้านนอกคงสภาวะเดิม ในการคำนวณหาค่าการถ่ายเทความร้อนในเนื้อวัสดุจะใช้หลักการของการนำความร้อน และผลของการถ่ายเทความร้อนนี้สามารถนำไปคำนวณหาความเค้นทางความร้อนในวัสดุได้โดยอาศัยหลักการของการหยืดหยุ่นทางความร้อนในวัสดุ จากการวิเคราะห์ พบว่า การประเมินค่าการถ่ายเทความร้อนของของไหลภายในท่อ จะสัมพันธ์กับความถี่ของการเปลี่ยนแปลงอุณหภูมิของของไหล ซึ่งสามารถหาผลลัพธ์ที่ถูกต้องได้โดยใช้วิธีการคำนวณทางตัวเลข (numerical method) และการคำนวณทางทฤษฎี (theoretical method) ผลที่ได้จากการถ่ายเทความร้อนของของไหลและความถี่ของการเปลี่ยนแปลงอุณหภูมิของของไหลที่พื้นผิวของวัสดุ สามารถนำมาประเมินค่าการเปลี่ยนแปลงของความเค้นในวัสดุได้

Abstract: At incomplete mixing area of high temperature and low temperature liquid near the surface of structures, temperature fluctuation of liquid gives thermal fatigue damage to wall structures. This phenomenon is called thermal striping. For designing of piping system, it is important to know thermal stresses of structure due to heat convection. In this study, authors proposed a simplified evaluation method to predict thermal stress from temperature fluctuation, for rational design against thermal striping. It is required to estimate structural responses to temperature fluctuation of fluid. The attenuation process is a thermal coupling problem between fluids and structures and has a sensitive characteristics to frequencies of temperature fluctuations were analyzed by FINAS, which is a computer program based on the finite element method by comparisons of theoretical method. When the inner surface of the pipe is due to heat convection of contained fluid with sinusoidal temperature fluctuation and the outer surface is kept insulated, temperature distribution of structure is analyzed by solving the equation of transient heat conduction. From these temperature distributions, induced thermal stresses in the structure are calculated by thermal elastic analysis. Frequency response characteristics of structures and its mechanism were investigated by both numerical and theoretical methods. Based on above investigation, a structural response diagram was derived, which can predict stress amplitude of structures from temperature amplitude and frequency of fluids.

Methodology: In order to grasp sensitivity of structural responses to frequency of fluid temperature fluctuations, the pipe wall due to sinusoidal fluid temperature fluctuation with various frequencies was analyzed by FINAS, which is a computer program based on the finite element method. Geometrical configuration and thermal boundary condition are as shown in Fig.1, where wall thickness L is 2 mm, inner diameter is 13.3 mm, and material is Type 304 stainless steel. The inner surface of the pipe is due to sinusoidal temperature fluctuation of fluid with constant amplitude ΔT_f as 251 °C (maximum temperature is 381 °C and minimum temperature is 130 °C) and the outer surface is kept insulated. This study assumed constant heat-transfer coefficient h, value of which was evaluated as 8.8517×10^{-6} kcal/mm^2*sec*°C from turbulent heat convection equation for liquid metal. Frequencies of sinusoidal temperature fluctuation of fluid were varied as 0.1 Hz, 1.0 Hz, 2.0 Hz, 5.0 Hz and 10 Hz. Temperature distribution of structure T_s (χ,t) was calculated by solving the equation of transient heat conduction with a finite element model consists of the isoparametric 8-node quadrilateral axisymmetric heat conduction element HQAX8 and the isoparametric 3-node heat-transfer element FCAX3 of FINAS code. Where x is depth from the surface, and t is time. From calculated temperature distribution, induced thermal stresses in the structure were solved by thermal elastic analysis with a finite element model consists of the isoparametric 8-node quadrilateral axisymmetric element QAX8 of the same code.

Results, Discussion and Conclusion: Heat conduction analysis results were as in Fig.2(a)-Fig.2(c), which show the temperature histories at inner and outer surfaces under various frequencies of sinusoidal temperature fluctuation. What is evident from these figures is that temperature amplitude decreases monotonously according to increase of frequency of fluctuation on both surfaces, among which the outer surface decreases rapidly than the inner surface. Its tendency is clear from Table 1, which shows temperature amplitude on the both surfaces. The results of thermal elastic analysis were as in Fig.3(a)-Fig.3(c), which show stress histories at the inner and outer surfaces under various frequencies of sinusoidal temperature fluctuation. The noteworthy point from above figures is that stress amplitude varies according to frequency and becomes the maximum at the particular frequency 1.0 Hz as in Table 2, even though amplitude of temperature fluctuation was constant. In order to understand a mechanism of phenomena, the numerical results are compared with theoretical calculations of a semi-infinite solid, where the surface is due to heat convection. Theoretical thermal responses at an inner surface to each frequency of liquid temperature fluctuation are calculated under the same heat convection boundary as the numerical analysis. Frequencies of liquid temperature fluctuation are 0.1 Hz, 1.0 Hz and 10 Hz. One-dimensional transient heat transfer theory with Equation (1) was applied to estimate stable periodical temperature response of a semi-infinite solid, with the boundary condition. The theoretical results were as in Fig.4(a)-Fig.4(c), which show the temperature response at the inner. The comparisons of temperature history at the inner surface between the numerical and the theoretical results were as in Fig.5(a)-Fig.5(c), where the surface is due to heat convection from temperature fluctuation of liquid. The temperature amplitude is observed to be decreased when the temperature fluctuation of liquid has high frequency. The temperature histories are approximately the same between the numerical and the theoretical results. The comparisons of temperature history at the outer surface between the numerical and the theoretical results were as in Fig.6(a)-Fig.6(c), where the theoretical temperature amplitude is smaller than numerical results. The theoretical results of temperature distribution across wall thickness, when time is $2\pi n/\omega$, temperature of the inner surface is maximum and minimum.

The effect of frequencies of liquid is well explained by equation (1). When frequency is high, both amplitude and spatial wavelength of temperature distribution would be reduced. It is illustrated by Fig.7(a). (b). Thermal stress is caused by temperature difference among surface are average. Following results are illustrated by Fig.7(b) and Fig.3(a)-(c). At frequency of temperature of liquid = 0.1 Hz, temperature amplitude is large. However, maximum stress is small. The reason is considered that wall thickness 2 mm is smaller than spatial wavelength of temperature distribution when frequency = 0.1 Hz. On the other hand, temperature amplitude of frequency of temperature of liquid = 1.0 Hz is larger than frequency of temperature of liquid = 10 Hz, and maximum stress of 1.0 Hz is larger. The reason is considered that wall thickness 2 mm is larger than special wavelength of temperature distribution for both 1.0 Hz and 10 Hz. In order to investigate thermal striping phenomena, 1-D structure response to sinusoidal temperature fluctuation of liquid has been studied through numerical and theoretical analysis. The result shows that frequency of liquid temperature fluctuation greatly affects the amplitude of structural response. When frequency is high, temperature amplitude becomes small. On the other hand, there is the frequency which induce the maximum thermal stress.

$$T_s = \frac{Ah^*}{\sqrt{(h^*+k)^2+k^2}} e^{-kx}\sin(\omega t - kx - \varepsilon) + Ti \qquad (1)$$

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(3) B. E. Gatewood, Ph.D, 1957, Thermal Stresses, McGraw-Hill book Co., London, PP 1-9.

Keywords: thermal striping, thermal stress, heat convection

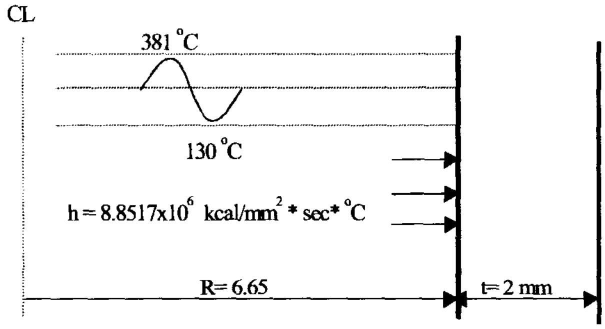


Fig.1 Thermal striping problem at piping system

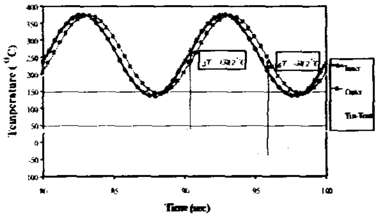


Fig.2(a) Temperature histories on the surfaces 0.1 Hz

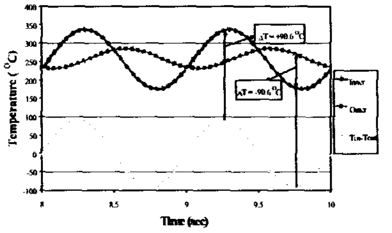


Fig.2(b) Temperature histories on the surfaces 1.0 Hz

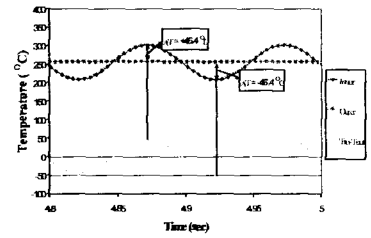


Fig.2(c) Temperature histories on the surfaces 10 Hz

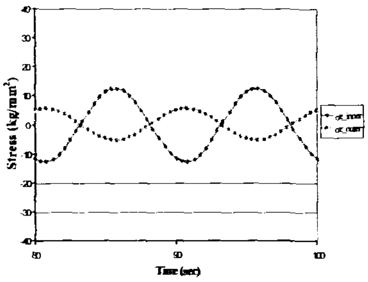


Fig.3(a) Stress histories on the surfaces 0.1 Hz

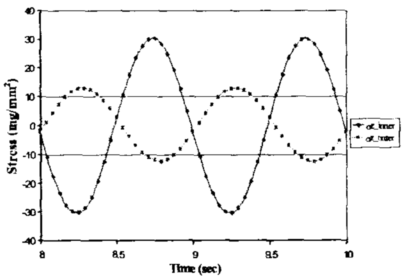


Fig.3(b) Stress histories on the surfaces 1.0 Hz

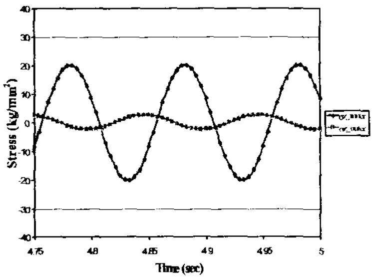


Fig.3(c) Stress histories on the surfaces 10 Hz

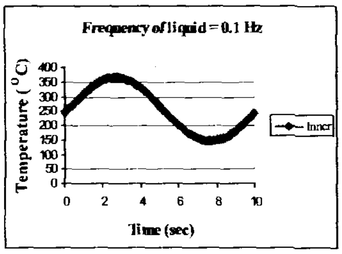


Fig.4(a) Theoretical results of temperature history at the inner surface 0.1 Hz.

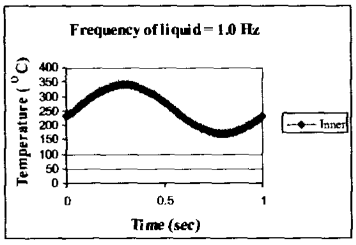


Fig.4(b) Theoretical results of temperature history at the inner surface 1.0 Hz.

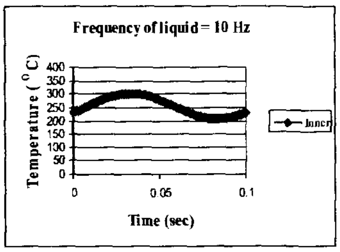
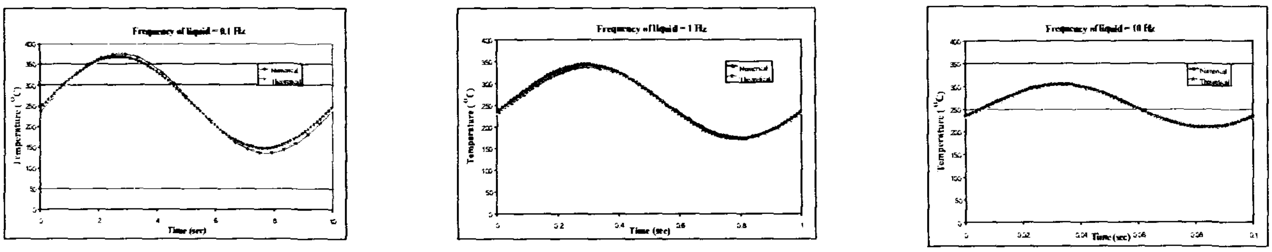
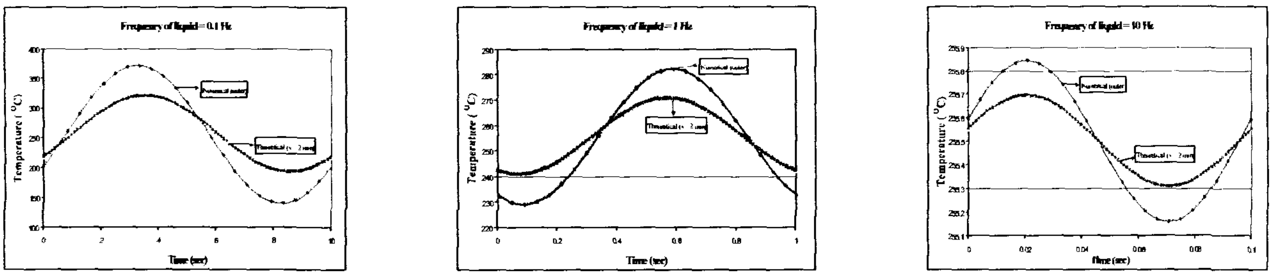


Fig.4(c) Theoretical results of temperature history at the inner surface 10Hz.



(a) Temperature histories 0.1 Hz (b) Temperature histories 1.0 Hz (c) Temperature histories 10 Hz

Fig.5 Comparisons of the numerical and the theoretical results at the inner surface



(a) Temperature histories 0.1 Hz (b) Temperature histories 1.0 Hz (c) Temperature histories 10 Hz

Fig.6 Comparisons of the numerical and the theoretical results at the outer surface

(a) Fig.7 Comparisons of temperature distribution at (a) Temperature distribution at time = $2\pi n/\omega$ (b)

(b) Temperature distribution when inner surface temperature is maximum and minimum

Table 1. Temperature difference between the inner and outer surface

Frequency value (Hz)	0.1	1.0	2.0	5.0	10
(Tin-Tout)max	38	90	82	59	46
Tinner at (Tin-Tout)max	299	333	328	313	302
Touter at (Tin-Tout)max	261	243	246	254	256

Table 2 Maximum and Minimum stress at the inner and outer surface in each analytical condition

Frequency	σz_Inner			σz_Outer		
	max	min	max-min	max	min	max-min
0.1 Hz	12.5	-12.5	25.0	5.47	-5.47	10.94
1.0 Hz	30.2	-30.2	60.4	12.6	-12.6	25.2
2.0 Hz	28.7	-28.7	57.4	10.5	-10.5	21.0
5.0 Hz	24.2	-24.2	48.4	5.32	-5.33	10.65
10 Hz	20.1	-20.1	40.2	2.50	-2.50	5.0