Investigation of the stress and strain state of clay pipes under fire condition

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Abstract

The focus of this paper is given to investigating the testing and evaluation method of stress and deformation behaviour of clay pipe elements like chimneys under cyclic high temperature. The experimental study on the temperature–time curves and on the radial deformation–temperature curves of a series of fire-resistant clay pipes was carried out. The tensile strength and the compressive strength, the elastic modulus before and after fire, the stress and deformation properties and the cracking behaviour of the clay pipes under fire conditions have been analyzed. The theoretical analysis corresponds well with the experimental results and tends to prove that the elastic deformation can be the most significant component in fixed-end clay pipes. This study is useful for evaluation of the stress–strain properties of ceramic pipes and provides a beneficial test method for the pipe member in small-scale or in full-scale tests under fire temperatures.

Keywords: High temperature–time curve; Radial deformation–temperature property; Stress–strain state; Clay pipe element

1. Introduction

Fire-resistant clay is widely used for producing pipe members for chimneys in Asia because clay is cheap and easy to produce. Chimneys in buildings may experience many prolonged cycles of high temperatures, and a mass of poisonous gas and smoke could be induced. With rapid development of the building industry in Asia, failure analysis on the clay pipe members under the fire becomes increasingly important, as it is directly related to the safety of the pipe structures and of human lives.

The objectives of fire-resistant clay pipe member like chimney under fire include a number issues such as the heat-transfer mechanisms, microstructure and chemical analysis and mixtures, cracking and smoke spread, manufacturing and recycling and material properties at elevated temperatures [1–4]. However, it is not intended in this study to present a complete knowledge of every aspect of the clay pipe chimney. Indeed, the focus is given to investigating the experimental and evaluation method of mechanic behaviour of clay pipe elements and to evaluate the radial deformation of the pipe members during the burning process under fire and to analyze what is the fraction of the elastic deformation of the total deformation, and to compare the theoretical analysis and the experimental values.

Although the variables on fire condition have been debated for long time, they can generally be considered to include the effect of temperature–time process, temperature difference and stress–strain relationship. The temperature–time development is the precondition for analyzing the temperature field and can significantly influence the deformation of materials or pipe members under fire. Several tests have been developed to investigate the thermal and mechanical behaviour after fire, including the stress and strain, thermal expansion or cracking and spalling in furnace tests [3–7]. However, they are mainly measured based on experiments in the fire-resistant furnace, which offers a relative even temperature environment around the specimens, or investigations of them are concentrated on the clay material properties and not on the behaviour of clay element. Measuring the real deformation of clay pipe members during the burning process under fire is an experimental challenge due to the low working temperature of normal linear variable differential transformer (LVDT-usually only up to 100 °C). A new type of high-temperature LVDT (HTLVDT),

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which can measure the deformation under the temperature up to 1200 °C, has been developed for investigating the deformation under high temperature. Furthermore, it is still an open question as to whether or not the simplified calculation based on the elastic theory could approximately analyze the stress and strain state of clay pipe members under fire. This theoretical calculation would be uncomplicated and acceptable for practical use for engineers.

Recently, the systematic investigation on the macro mechanic behaviour of the clay pipe elements under the fire conditions, especially the study on the stress and strain behavior of the clay pipe under cyclic high temperature, is very rare due mainly to the difficulty of the acquisition of the deformation data under fire conditions. In order to investigate the thermal behavior for various layers of the pipe member under fire conditions, a high-temperature burning test method has been performed based on the German Guideline [8].

2. Experimental

The experiments were carried out in the Institute of Building Materials, Innsbruck University. The composition of the fire-resistant clay materials was analyzed and reported in Table 1.

The test set-up is demonstrated in Fig. 1a and b, the interior of the specimen is the fire-resistant clay pipe and the exterior is the heat-insulating asbestos layer. The inner radius of the clay pipe is 90 mm, the outer radius is 110 mm, and the thickness is 20 mm.

As shown in Fig. 1b, the pipe specimen is set up on the platform through which the gas fire can be led into the pipe. The end of each pipe is fixed with a pedestal. The temperatures of the gas and the different layers of the pipe are measured by the high-temperature thermocouple, and the radial deformations of the pipe in four directions are measured by the high-temperature LVDT. All the pipes are wrapped by the 40 mm asbestos layer for heating isolation during the burning experiment and to prevent the possible deformation of the steel frame due to the change of ambient temperature. The section of the measured points was 1000 mm from the exit of the gas line. The two-circle burning test is carried out according to German Guideline [8,9]. The whole temperature-rising process of the pipe is controlled by the gas temperature and is divided into two similar stages. As shown in Fig. 2, the heating rate is 100 °C/min, the temperature of the gas increases up to 1000 °C in 10 min, after that it remains stable 30 min at 1000 °C then falls down naturally to the room temperature. The second stage is the same as the first one and the two stages are carried out successively.

Table 1
Composition of the clay materials (wt.%)

	Composition
SiO_2	67
Al_2O_3	27.5
Fe_2O_3	1.4
CaO	0.3
MgO	0.5
Na_2O	0.2
K_2O	1.6
TiO_2	1.5

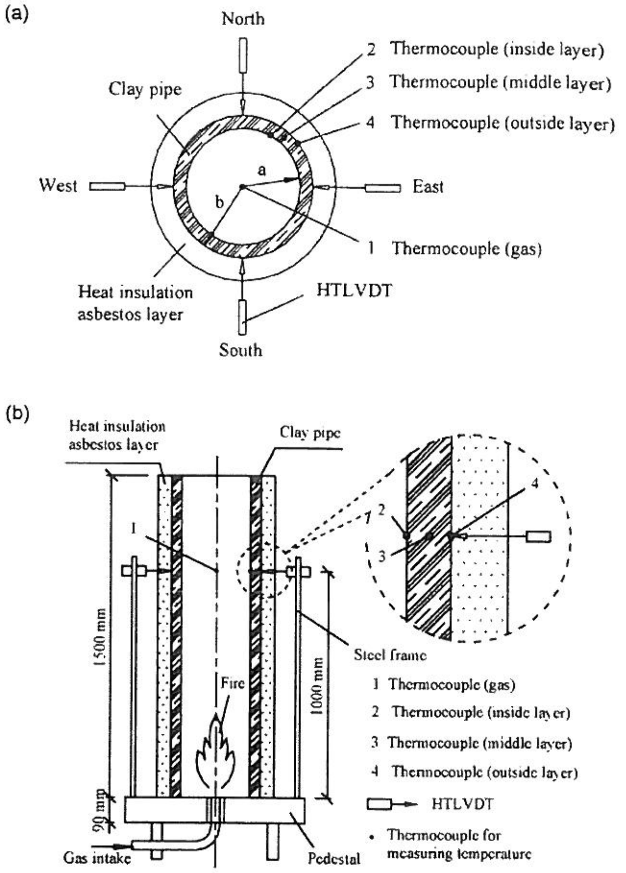

Fig. 1. (a) Cross-section of specimen and the measuring position. (b) Vertical section of the testing set-up and the measuring position.

3. Experimental results and theoretical analysis

3.1. Experimental results

3.1.1. Experiments of strength and E-modulus

The tensile strength, the compressive strength and the elastic modulus before and after the first burning process have been

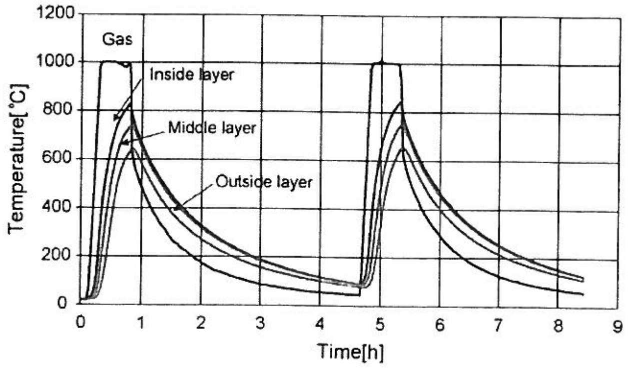

Fig. 2. Temperature–time curves.

Table 2
Comparison of the mechanical properties before and after burning process

	Before burning	After burning
Elastic modulus (kN/mm^2)	43	21.4
Compressive strength (N/mm^2)	97	46.7
Tensile strength (N/mm^2)	6.7	2.4

tested and are compared in Table 2. The average coefficient of thermal expansion of clay materials within the temperature range of 20–600 °C is: $\alpha \approx 8.3 \times 10^{-6}$ [7,9], with Poisson's ratio $\mu \approx 0.2$. It can be seen that the fire-resistant clay materials demonstrate very good post-fire properties compared to concrete. The average E-modulus before and after the first burning stage has been used for the elastic analysis, and the elastic analysis is only valid for the elastic deformation of the first burning stage because the pipe begins to cracking at the end of the stable phase of the gas temperature.

3.1.2. Temperature–time curves

The fire growth rate is a significant influence factor that determines the fire severity. In accordance with the German Guideline [8,9], Fig. 2 presents the temperature–time curves of the heated gas and the inside layer, the middle layer and the outside layer of the pipe. The temperature decreases from the inside layer to the outside layer gradually. In the two-cyclic burning test, the temperatures of the inside layer, the middle layer and the outside layer reach the maximum value at the beginning of the decrease in the gas temperature, and the changes of the pipe's temperatures lag behind the change of the gas temperature.

In the first phase, the maximum temperature difference between the inside layer and the outside layer is about 360 °C. It happens at the stable phase of the gas temperature. In the second phase, the maximum temperature difference is about 340 °C, it also happens at the stable phase of the gas temperature.

3.1.3. Radial deformation

Fig. 3 shows the typical relationship between the radial deformation and the temperature of the middle layer of the clay pipe 2 (CP-2 in Table 3), which is very close to the average value of all experimental results.

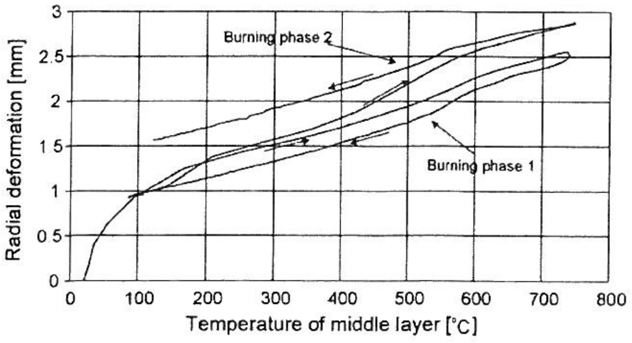

Fig. 3. Radial deformation–temperature curve.

Table 3
Experimental values and statistic analysis of clay pipes

Specimen	δ_{m1}	δ_{m2}	δ_{r1}	δ_{r2}	Icr
CP-1	3.04	3.02	0.12	0.19	0.07
CP-2	2.56	2.88	0.92	1.56	0.64
CP-3	2.38	2.37	0.56	0.93	0.37
CP-4	2.91	2.93	0.47	0.69	0.22
CP-5	2.55	2.61	0.21	0.33	0.12
CP-6	2.52	2.54	0.35	0.57	0.22
CP-7	2.22	2.35	0.17	0.28	0.11
CP-8	2.68	2.64	0.71	0.98	0.27
CP-9	2.32	2.35	0.59	1.03	0.44
CP-10	2.75	2.85	0.88	1.47	0.59
CP-11	2.33	2.47	0.74	1.16	0.42
CP-12	2.28	2.39	0.83	1.39	0.56
CP-13	2.81	2.83	0.61	0.95	0.34
CP-14	2.34	2.36	0.41	0.61	0.2
Mean value	2.55	2.61	0.54	0.87	0.33
S.D.	0.26	0.24	0.26	0.44	0.18
COV	0.10	0.094	0.49	0.51	0.57

The radial deformation experiences two cycles along with the change of the temperature. In the first burning process, when the temperature of the middle layer reaches the highest value, the radial deformation reaches at the maximum of 2.56 mm, while the gas temperature is at the beginning of falling phase and the pipe temperature is at the end of rising phase. When the burning gas is shut off, the radial deformation recovers gradually while the pipe temperature decreases also, but the residual radial deformation of 0.92 mm remains. Similarly, in the second burning process, when the temperature of the middle layer reaches the highest value, the radial deformation arrives at the maximum of 2.88 mm as illustrated in Fig. 3. The residual radial deformation of 0.64 mm in the second burning process is less than the unrecoverable radial deformation of 0.92 mm in the first burning process; the total residual radial deformation of both burning processes reaches 1.56 mm (see Fig. 3).

Fig. 4 shows the relationship between the radial deformation of the pipe and the temperature difference between the inside layer and the outside layer. In the two burning processes, the radial deformation did not reach the maximum when the temperature difference reaches the maximum.

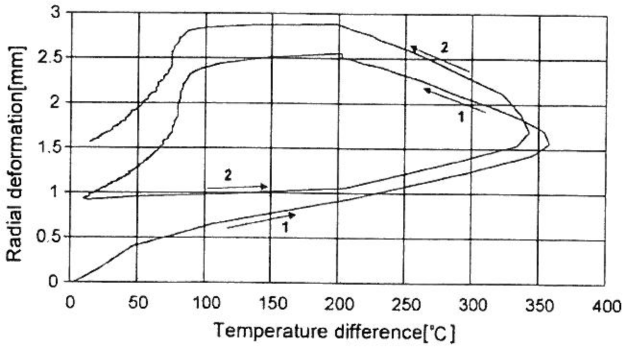

Fig. 4. Radial deformation–temperature difference curve.

Combined with Fig. 3, it can be seen that the temperature has a stronger influence on the radial deformation than the temperature difference. For this reason the temperature of the pipe is the major factor for the radial deformation.

The results of the maximum radial deformation in the first burning process (δ_{m1}) and in the second burning process (δ_{m2}), the residual radial deformation after the first burning process (δ_{r1}) and the residual radial deformation after the second burning process (δ_{r2}) of all 14 clay pipes (CP) and the increment (Icr) from δ_{r1} to δ_{r2} are given in Table 3. The statistic analysis for the experimental results like the standard deviation (S.D.) and the coefficient of variation (COV: standard deviation/mean value) of δ_{m1} and δ_{m2}, δ_{r1} and δ_{r2} and Icr has been carried out and also presented in Table 3.

It can be seen that the coefficients of variation (COV) of the measured maximum radial deformations in both burning processes are 10% and 9.4%, it means a relative small dispersion of the experimental results. The mean value of measured maximum radial deformation of the first burning process is almost equal to that of the clay pipe 2 (CP-2) as shown in Figs. 3 and 4. The coefficients of variation and the Standard Errors of the mean prove that the experiments are carried out successfully with small scatter. The analysis of the residual radial deformation (δ_{r1}, δ_{r2} and Icr) demonstrates that the total residual radial deformation of the clay pipe will be enlarged with increasing number of the cycles, however, the increment of the residual radial deformation will decrease.

3.2. Simplified calculation of the stress and strain under burning

The clay pipe materials change from the elastic state into the non-elastic state, if a crack occurs. In spite of that, a simplified evaluation [7] based on the elastic theory was undertaken, in order to analyze the stress–strain state approximately, because an exact mathematic/mechanic solution with differential equation for non-elastic state is too complicated and very difficult. In the stable phase of the gas temperature, the thermal stress of the pipe is calculated according to the plane strain problem of the thermal stress in the elasticity theory. In the stable temperature field, $\partial T/\partial t = 0$, a and b are the radius of the interior side and the exterior side of the pipe, respectively, T_a and T_b are the temperatures of the pipe inside and pipe outside layers, respectively, and E, μ and α are the elastic modulus before and after the first burning exposure, the Poisson's ratio and the thermal expansion coefficient (see Section 3.1.1), respectively. For the temperature stress of the thin-shell cylinder in two-dimensional temperature field, the expressions in the polar coordinates is given as follows [10]:

- Radial stress:

$$\sigma_r = -\frac{E\alpha(T_a - T_b)}{2(1-\mu)}\left(\frac{\ln(b/r)}{\ln(b/a)} - \frac{(b^2/r^2) - 1}{(b^2/a^2) - 1}\right) \qquad (1)$$

- Hoop stress:

$$\sigma_\theta = -\frac{E\alpha(T_a - T_b)}{2(1-\mu)}\left(\frac{\ln(b/r) - 1}{\ln(b/a)} + \frac{(b^2/r^2) + 1}{(b^2/a^2) - 1}\right) \qquad (2)$$

Vertical stress:

$$\sigma_Z = -\frac{E\alpha(T_a - T_b)}{2(1-\mu)}\left(\frac{2\ln(b/r) - 1}{\ln(b/a)} + \frac{2}{(b^2/a^2) - 1}\right) \qquad (3)$$

The radial strain (ε_r) and the hoop strain (ε_θ) are given in equations (4) and (5), respectively:

- Radial strain:

$$\varepsilon_r = \frac{(1-\mu^2)}{E}\left(\sigma_r - \frac{\mu}{1-\mu}\sigma_\theta\right) + (1-\mu)\alpha T \qquad (4)$$

- Hoop strain:

$$\varepsilon_\theta = \frac{1-\mu^2}{E}\left(\sigma_\theta - \frac{\mu}{1-\mu}\sigma_r\right) + (1-\mu)\alpha T \qquad (5)$$

Replace Eqs. (1) and (2) in (4) and (5), respectively, we get ε_r and ε_θ. The sum of the outside layer radial deformation (δ_{mb}) in four directions is as follows: $\delta_{mb} = 4r_b(\varepsilon_\theta)_{r=b}$. In the stable phase of the gas temperature (the stable temperature field) of the first burning process, the condition at the largest radial deformation is chosen, in which the temperature of the inside layer T_a is 832 °C and the temperature of the outside layer T_b is 630 °C (see Figs. 3 and 4). So the calculation is as follows:

$(\sigma_r)_{r=a} = (\sigma_r)_{r=b} = 0$

so the radial stress is zero.

$(\sigma_\theta)_{r=a} = -34.2$ N/mm^2 (compressive stress) $= (\sigma_z)_{r=a} < 46.7$ N/mm^2 (compressive strength of the clay after burning in Table 1), so the hoop stress of the inside layer is equal to the vertical stress, they are all the compressive stresses, and smaller than the compressive strength of the material.

$(\sigma_\theta)_{r=b} = 29.9$ N/mm^2 (tensile stress) $= (\sigma_z)_{r=b} > 2.4$ N/mm^2 (tensile strength of the clay after burning, Table 1), so the hoop stress of the outside layer is equal to the vertical stress, they are all the tensile stress and larger than the tensile strength which indicates that the cracks firstly occur on the outside layer of the pipe, then gradually extend to the inside layer, and finally cause the fracture of the specimen.

The hoop strain of the inside layer $(\varepsilon_\theta)_{r=a} = 5.93 \times 10^{-3}$, and the radial strain of the outside layer $(\varepsilon_\theta)_{r=b} = 6.28 \times 10^{-3}$, so the theoretical calculated radial deformation: $\delta_{mb} = 4r_b(\varepsilon_\theta)_{r=b} = 2.42$ mm.

The average radial deformation of the first burning stage was measured to be 2.55 mm (see Table 3). The difference between the mean value and the calculated value is only about 5%, and the difference between the maximum value of clay pipe 1 (CP-1) and the calculated value is about 20%. It means that the calculated value is relatively close to the mean value of measured radial deformation because of the high brittleness of clay materials, and therefore, the simplified calculation according to elastic theory is acceptable in the practice—at least for the first burning process. For the study on thermal under fire, some variation in thermal conditions could be expected.

3.3. *Discussion*

The experimental study on the measuring of the temperature–time and the radial deformation–temperature curves has been carried out successfully. The elastic analysis is valid for the elastic part of the first burning stage because the pipe begins to cracking at the end of the stable phase of the gas temperature. The accuracy of the theoretical evaluation depends on the choice of the thermal expansion coefficient α and the Poisson's ratio μ, E-Modulus and other factors. The average unrecoverable radial deformation of the first burning process was about 0.54 mm (see Table 3). It means that the elastic calculation could underestimate the radial deformation. However, one of the important preconditions for any technical analysis and practical using is to know how much radial deformation could be underestimated, and then that difference may be resolved by adding a safety-factor.

All chimneys experience a large number of heating cycles. It is difficult and expensive to do more burning cycles, only the two-circle burning test lasts 8.5 h. The behaviour after more than two burning stages could be deduced from the two cycles of test. The residual radial deformation will be enlarged; the pipes will get more cracks. The gas tightness of the pipe declines. The strength and E-modulus, the factor of thermal properties will be influenced by the number of heating cycles. The theoretical analysis corresponds well with the experimental results and demonstrates that the elastic deformation could be the main part of measured thermal deformation in end-fixed supported pipes.

4. Conclusions

The results of this study yield the following conclusions:

(1) An experimental method is established based on using high-temperature LVDT, and the results indicate that this method is suitable, cheap and easy to use to measure the radial deformation of pipe members and can be used in small-scale or full-scale pipe elements under fire conditions.
(2) The radial deformation reaches the maximum value when the pipe temperature reaches its highest value.
(3) The pipe temperature has stronger effect on the radial deformation than the temperature difference between the inside and outside pipe layers. The residual radial deformation occurs in both of two cyclic burning stages, and the residual radial deformation of the second burning process is less than the unrecoverable radial deformation of the first process.
(4) The thermal stress–strain state of pipe members could be analyzed approximately by means of the elastic theory. The theoretical analyzes with finer scatter agree well with the measured experimental values and demonstrate that the elastic deformation is the main part in the measured deformation of fixed-end supported clay pipes.
(5) The tensile stress occurs on the outside layer of the pipe, while the inside layer is subjected to compressive stress. The tensile stress of the pipe outside layer is larger than the tensile strength of the materials, and causes the vertical cracks firstly on the pipe outside, those cracks extend gradually to the inside layer and cause finally the failure of the pipe.
(6) This study can be useful for evaluation of the stress–strain properties of pipe elements and provides a beneficial reference for the pipe member of other ceramic materials in small-scale or in full-scale under fire conditions.

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