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REVIEW ARTICLE

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Cross bore geometry configuration effects on stress concentration in high-pressure vessels: a review

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Abstract

The aim of this study was to establish the effect of cross bore configuration geometry on stress concentration in cross-bored high-pressure vessels. The cross bore geometry parameters with adverse effects on stress concentration include cross bore size, shape, location, obliquity, and thickness ratio. However, there were no conducted studies on the optimal combination on these geometric configuration parameters that give minimum stress concentration, although the cited phenomena are common in pressure vessel design. Therefore, there is need for further research on the optimal geometric configuration in a high-pressure vessel under elastic, elastoplastic, and plastic operating conditions with regards to the selected cross bore configuration parameters. Optimization of the stress concentration factor will greatly improve the design of high-pressure vessels.

Keywords: High-pressure vessels, Cross bore geometry, Stress concentration factor

Introduction

High-pressure vessels are air-tight containers (Nabhani, Ladokun, & Askari, 2012), mostly cylindrically, conically, ellipsoidally, or spherically shaped (Hyder & Asif, 2008), that are used to store a large amount of energy (Kihiu & Masu, 1995). They are termed as thick walled when their ratio of thickness and internal radius exceeds $^{1}/_{20}$ (Nabhani et al., 2012). The basic pressure vessel design takes into account the vessel failure modes, induced stresses, selection of materials, the surrounding environment, and stress concentration (Hyder & Asif, 2008). Pressure vessels are used for various applications in thermal and nuclear power plants, the process and chemical industry, space, the ocean depth, and fluid supply in industries (Jeyakumar & Christopher, 2013; Kharat & Kulkarni, 2013).

Pressure vessels are usually loaded with working fluid at high pressures and temperatures commonly referred to as thermo-mechanical loading (Nayebi & Sadrabadi, 2013). This loading induces static, dynamic, and thermal stresses on the cylinder wall due to the variation in pressure and temperature, respectively (Choi, Fujiyama, Kim, & Song, 2012). However, due to the discontinuities in the cylinder, the stress distribution along the cylinder wall is not uniform. These discontinuities such as geometric, loading, and metallurgical create regions of high stress that are referred to as stress concentrations. The stress concentrations due to static, dynamic, and thermal stresses are calculated using dimensionless factors called the stress concentration factor (SCF), dynamic stress concentration factor (DSCF), and the thermal stress concentration factor (TSCF), respectively (Babu, Ramana, & Rao, 2010). High values of these dimensionless factors are some of the causes of pressure vessel failures (Nabhani et al., 2012) or reduced operating life (Choi et al., 2012). Failures of the pressure vessel are usually catastrophic and may lead to loss of life, damage of property, or pose a health hazard (Kharat & Kulkarni, 2013; Masu, 1997). However, these catastrophic failures can be avoided when the design and manufacture of pressure vessels is done in accordance with standard pressure vessel design codes (Kihiu & Masu, 1995). However, these codes only give sets of wall thickness and their corresponding hoop stresses are below the allowable working stresses without any detailed stress analysis (Kihiu, Rading, & Mutuli, 2004). This practice has led to

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the use of high safety factors in pressure vessel design ranging from 2 to 20 (Masu, 1997). This phenomenon results in uneconomical use of material which translates into the high manufacturing cost of pressure vessels. Other processes such as autofrettage and shakedown (Li, Johnston, & Mackenzie, 2010) are also performed at the manufacturing stage of pressure vessels to increase their strength (Kihiu et al., 2004). However, it is likely that a more detailed stress analysis will obviate the need for autofrettage and shakedown, with the accompanying reduction in the manufacturing cost (Nziu & Masu, 2019).

In practice, holes or openings are drilled in the wall of plain pressure vessels (Masu, 1998). A single hole in one side of the vessel is known as a side hole, whereas two transverse holes in both sides of the vessel are known as cross holes or cross bores (Makulsawatudom, Mackenzie, & Hamilton, 2004; Peters, 2003). Cross bores are referred to as radial when they are drilled at the center axis of the vessel. On the other hand, cross bores are referred to as offset when drilled at any other chord away from the vessel centroidal axis (Makulsawatudom et al., 2004; Nziu & Masu, 2019). Cross bores are of different sizes and shapes. The size ranges from small drain nozzle to large handholds and manholes such as tee junctions (Kharat & Kulkarni, 2013). The common cross bore shapes are circular and elliptical (Nagpal, Jain, & Sanyal, 2012). According to Steele et al. (1986), a circular cross bore is termed as small when the ratio of the cross bore to main bore diameter is ≤ 0.5. However, when the same bore ratio ranges from ≥ 0.5 to ≤ 1, the cross bore is termed as large. In contrast, the description of elliptical-shaped cross bore is centered on the diameter ratio and the orientation of major and minor diameters with the principal axes of the cylinder (Cole, Craggs, & Ficenec, 1976; Harvey, 1985).

Cross bores give provision for fitting relief and safety valves, bursting disks, gas inlets, flow circuit meter, temperature and internal pressure measurement, inspection covers, lubrication, etc. (Kihiu & Masu, 1995). As a result, cross bores are inevitable in pressure vessel design (Kihiu & Masu, 1995). Nonetheless, these openings introduce geometric discontinuities that alter the uniform stress distribution in the cylinder walls (Kharat & Kulkarni, 2013). The geometric discontinuities act as stress raisers, thus creating regions of high-stress concentration especially near the openings (Masu & Craggs, 1992). Due to these high-stress regions, the elemental stress equations in thick walled vessels cease to apply (Kharat & Kulkarni, 2013).

Stress concentrations at these regions are determined by a dimensionless factor called the stress concentration factor (SCF) (Kharat & Kulkarni, 2013). Some authors refer to SCF as the effective stress factor (ESF) (Moffat, Mwenifumbo, Xu, & Mistry, 1991). SCF can be determined for various stress criteria depending on the working conditions of vessels such as maximum tensile stress (hoop), Von Mises, or Tresca (Nziu, 2018). Theoretical hoop SCF is determined using the relationship given in Eq. (1) as detailed in Masu and Craggs (1992) and Kharat and Kulkarni (2013).

$$\mathrm{SCF} = \frac{\text{Maximum hoop stress in a cross bored cylinder}}{\text{Corresponding hoop stress in a cylinder without a cross bore}} \tag{1}$$

SCF is closely linked to persistent problems encountered in the design of pressure vessels such as fractures, fatigue failures, and local yielding (Nziu, 2018). Therefore, it is a very important parameter to be considered during the design of pressure vessels (Nziu & Masu, 2019). According to Cole et al. (1976), high values of SCF act as points of weakness leading to a reduction in the vessel strength as well as its fatigue life. This consequently may reduce the pressure carrying capacity of the pressure vessel by up to 60% (Masu, 1989) in comparison to a plain vessel without cross bores. These findings justify the need for pressure vessel designers to ensure minimum SCF. For instance, in the design and manufacture of components, such as shafts, valves seats, forging, etc., blending geometry technology has been extensively used to reduce the SCF (Masu & Craggs, 1992).

Research studies with a view to reducing SCF across the cross bore have been carried out. The following is a general overview of the studies conducted on stress analysis. Mackerle (1996) comprehensively reviewed 632 published journal articles between 1976 and 1996 on “linear and nonlinear, static and dynamic, stress and deflection analyses,” but only 9% of the published articles were on stress analysis. Mackerle (1999, 2002, 2005) repeated the same study and published three more articles covering the period from 1996 to 1998, 1998 to 2001, and 2001 to 2004. On each period mentioned earlier, the number of articles reviewed on the same study was given as 173, 140, and 128. However, the studies on stress analysis were found to be 15%, 11%, and 6%, respectively.

More recently, Kharat and Kulkarni (2013) reviewed 41 published journal articles on stress concentration. However, only 27% were on SCF around cross bore openings. Seventy-six percent of the articles reviewed in this study were on thick pressure vessels. Interestingly, the study recommended the need for more research in stress concentration on thin-walled cylinders. This recommendation contradicted another study conducted by Diamantoudis and Kermanidis (2005) which concluded that most industrial applications use thick-walled high-pressure vessels. They argued that the use of pressure vessel design codes during the manufacture of high-pressure vessels advocates for large safety factors, hence increase in material thickness. In this regard, most of the industrial applications use thick-walled cylinders; hence, more research ought to be done on them.

In cross-bored cylinders, the SCF depends on the geometric configuration of the cross bore. The parameters of cross bore geometry with a major effect on stress concentration include cross bore size, shape, location, angle of obliquity, and thickness ratio (Nziu, 2018). Numerous studies on the effects of cross bore geometry configuration on stress concentration in high-pressure vessels have been conducted. However, despite close interrelation of these geometric parameters, the majority of the reviewed studies addressed each parameter separately. Besides, studies on optimization of cross bore geometry parameters have not been adequately investigated.

Therefore, this review article focuses on the effects of the geometric configuration of a cross bore on stress concentration in high-pressure vessels, with the aim of investigating the optimum parameters. In addition, a review of methods of stress distribution measurements was also done since it falls within the ambit of this paper.

Measurement of stress distribution

Several techniques namely, experimental, analytical, and numerical (also known as computational), are used for the analysis of stress distribution in high-pressure vessels. Experimental techniques use various methods such as photo-elasticity, grid, brittle coating, moiré, strain gage, among others to obtain an experimental solution. In experimental techniques, prototype specimens are mainly used for experimental testing. However, the use of prototype specimens instead of models, together with equipment and labor costs, makes the experimental techniques more expensive than the other methods (Masu, 1994).

Theories of elasticity, elastoplastic, or plasticity are used in analytical methods (Zhang et al., 2012) to analyze the stresses of certain simple geometrical shapes. The accuracy of the arising solutions depends on the assumptions of the theory and the boundary conditions used. The solutions obtained from these methods are referred to as exact or analytical or closed-form solutions (Nagpal et al., 2012). These closed-form solutions are obtained using various mathematical methods (Dharmin, Khushbu, & Chetan, 2012) such as complex function theory (conformal mapping, boundary collocation, Laurent series expansion, complex variable approach, etc.) and integral transforms (Fourier, Laplace, Mellin, Hanckel, Eigen function expansion, etc.). Lately, computer softwares such as Matlab and Maple are used to solve the generated simultaneous equations by the analytical methods.

Lastly, numerical methods use packages such as finite element analysis (FEA), finite difference, finite volume, boundary integral element (BIE), and mesh-free methods for stress analysis (Masu, 1989; Nagpal et al., 2012). The solutions obtained by these numerical methods are referred to as approximate numerical solutions. Each of these methods is suitable for various applications. For instance, the mesh-free method is used to determine the stress distribution in elements with discontinuous or moving boundaries, whereas the BIE method is used to determine the stress distribution at the surface of the element (Nagpal et al., 2012).

Some of the FEA commercial-based software commonly used in stress analysis are ANSYS, COSMOL, DYNA, ABAQUS, PAFEC 75, ADINA, NASTRAN and LUSAS (Nagpal et al., 2012). The choice of a particular software depends on the availability, the type of stress analysis to be performed, the element to be analyzed, and the required depth of accuracy, among other factors (Nagpal et al., 2012). However, some of the software packages applications are common.

FEA numerical method has been more extensively used for stress analysis in the last decade than both experimental and analytical methods (Kharat & Kulkarni, 2013). This is due to its ability to perform simulation and give highly accurate results (Zhang et al., 2012) that are comparable with those from its competitors (experimental and analytical methods). The results given by FEA are independent of the presence of any geometric parameters. The FEA method is also more convenient, faster, cheaper, and easy to use (Kharat & Kulkarni, 2013). The speed and convenience of use with results of the acceptable level of accuracy makes numerical methods more preferable when compared to those obtained from experimental and analytical methods (Zhang et al., 2012). However, the accuracy of numerical solutions depends on the correct usage of the type of element, mesh density, accurate modeling of the domain, material, loading, and boundary conditions (Qadir & Redekop, 2009). Besides, in symmetrical structures, the FEA analysis is performed using only a quarter or an eighth of the entire cross section (Masu, 1991). This technique reduces both the computer memory and the run time by up to 75% (Kihiu & Masu, 1995).

Effects of geometry configuration of a cross bore on stress concentration in high pressure vessels

Some of the geometric design configurations that affect SCFs in high-pressure vessels are the cross bore size, shape, location, obliquity, and thickness ratio. The following is a brief discussion of these design parameters.

Cross bore size

Gerdeen (1972) studied the relationship between SCFs and different ratios of cross bore to main cylinder bore size in thick cylinders having thickness ratios of 1.5, 2, 3, 4, and 6. The results showed an increase in SCFs as the ratio of cross bore to main cylinder bore increases. These findings compared well to other findings by Masu (1997) and Makulsawatudom et al. (2004). Masu (1997) studied the effects of cross bore size on stress distribution in thick-walled cylinders with a thickness ratio of 2. The study reported that for a particular thickness ratio, the SCF increases with increasing cross bore size.

Further extrapolation of the results presented by Gerdeen's equation revealed that the minimum SCF occurred when the ratio of cross bore to cylinder bore size was equal to 1. The Gerdeens' findings were also contradicted by another similar study conducted by Comlekci, Mackenzie, Hamilton, and Wood (2007). Comlekci et al. (2007) studied thick cylinders with a thickness ratio of 1.4, 1.5, 1.6, 1.75, 2.0, 2.25, and 2.50, and cross bore to cylinder bore size ratios ranging from 0.01 to 0.25. They reported minimum the SCF to occur between the size ratio of 0.1 and 0.2.

Hyder and Asif (2008) conducted another similar study using the Von Mises theory on thick cylinders with a thickness ratio of 2.0. They reported optimal cross bore sizes of 8 mm and 10 mm for cylinders with an internal diameter of 200 mm and 300 mm, respectively. This meant that the optimal size ratio occurred when the cross bore to cylinder bore ratios were at 0.03 and 0.04.

Cross bore shape

Kihiu and Masu (1995) studied the effect of chamfers on the distribution of stress in cross-bored thick-walled cylinders under internal pressure using FEA. They reported that incorporating chamfers, blend, or radius entry on circular cross bore, cause stress redistribution that leads to a reduction in SCF. A SCF reduction of up to 34.2% was noted at the main bore due to the introduction of chamfers in comparison with plain cross bores. A further reduction in SCF can be achieved by either varying the chamfer angle or the length or combinations thereof. However, the study concluded that the percentage reduction in SCF due to the introduction of chamfers depended on cylinder thickness, cross bore radius, chamfer length, and angle. For instance, the optimal SCF for cylinder thickness ratio of 2 was found to be 2.17 at the cross bore radius of 1 mm and chamfer angle of 50°. Masu (1989) studied the effect of varying chamfer depth on stress distribution. The study concluded that stress magnitude decreases with decreasing chamber depth.

Kihiu (2002) carried out another study on stress characterization in cross-bored thick-walled cylinders. The study investigated the effects of the introduction of chamfers and radiused entry in plain cross bores. The study reported that the radiused entry had lower SCF than chamfers. This observation was in line with an earlier study conducted by Masu (1989) on the effects of varying blending radius on stress distribution. The study concluded that stress distribution along blended radiused cross bore was almost the same as that of plain cross bore, particularly when the blend radius size is small.

As reported by Kihiu and Masu (1995), the stress redistribution on the vicinity of the cross bore due to the introduction of chamfers and blends also gives rise to other points of peak stresses along the chamfer, especially at the crotch corner. The values of the peak stresses occurred at 12.5 mm from the cross bore and were 140% greater than those at the cross bore intersection. These high-peak stresses are some of the causes of reduced fatigue life in high-pressure vessels (Comlekci et al., 2007). These findings are in line with another latter study done by Makulsawatudom et al. (2004).

Makulsawatudom et al. (2004) studied peak stress due to the introduction of blend radius and chamfers for radial circular and elliptical cross bores. The study compared their results with those obtained from a plain cross bore. They reported that the introduction of chamfers generates high-peak stresses for both circular and elliptical cross bores, with plain cross bores having the lowest peak stresses. This finding was in agreement with an earlier study done by Harvey (1985) on elliptical-shaped cross bores in thin cylinders. The study by Harvey (1985) had reported an optimal SCF of 1.5, when the diameter ratio of a radial elliptical cross bore was 2. The cross bore configuration was such that the minor axis diameter was perpendicular to the direction of the hoop stress.

Generally, for all the three cases studied Kihiu and Masu (1995); (Masu, 1989) and Makulsawatudom et al. (2004)) the peak stresses for elliptical radial cross bore were lower than those of circular cross bore. Moreover, the three studies established that carefully polished chamfers at the intersection of the main cylinder and the cross bore also reduces SCF further. The polished chamfers at the intersection are usually carried out using spark erosion techniques (Masu, 1989).

Cole et al. (1976) and Makulsawatudom et al. (2004) reported that SCFs can be reduced by making an elliptical-shaped cross bore positioned along the cylinder radial line instead of round-shaped cross bores. The two studies also reported that SCFs reduce when round-shaped cross bores are offset by an appropriate distance from the cylinder radial lines. According to Cole et al. (1976) offsetting the position of the cross bore from the radial line also improves the fatigue life of the cylinder by up to 170%.

Makulsawatudom et al. (2004) pointed out that there was a relatively small difference of up to 5% in the values of SCFs obtained, when elliptical-shaped cross bores were drilled in the offset position from the radial line instead of circular ones. They recommended the use of circular shaped holes at the offset position instead of elliptical ones, due to their low manufacturing cost.

Carvalho (2005) studied the effects of U-shaped notches on SCFs in internally pressurized cylinders using FEA. The study concluded that, regardless of the size, notches alter the stress distribution curves in the whole cross section, creating high regions of stress concentration. In this regard, the study recommended that the introduction of notches in any pressure vessel should be avoided.

Adenya (2010) studied stress concentration factors in a high-pressure vessel with elliptical radial cross bores. They reported a reducing effect on SCF, when an elliptical-shaped cross bore whose major axis was perpendicular to the cylinder axis and was positioned in the transverse plane of the cylinder. At this transverse position, the minimum SCF was found to be < 2 (a decrease in SCF magnitude in comparison to a similar circular radial cross bore whose SCF is given as 2.5). The study concluded that, the maximum SCFs occurred when the major axis of elliptical cross bore lays in longitudinal plane. Whereas, the minimum SCFs occurred when the major axis of elliptical cross bore lays in transverse plane.

Cross bore location

A configuration illustrating an offset cross bore is shown in Fig. 1.

The offset distance is measured from the central axis of the main cylinder to the transverse axis of the cross bore. However, for effective comparison of results with the existing literature, this offset distance is converted to either an offset location ratio or included angle. The offset location ratio is obtained by dividing the actual offset distance with the radius of the main bore, whereas the included angle is calculated from the trigonometric relationship between the two distances.

As reported by Little and Bagci's (1965) study, small offset cross bores in the transverse plane of the cylinder generate positions of major and minor axes. Indeed, when an offset cross bore is viewed from the direction of the main bore, its shape at the intersection of the main bore and the cross bore resembles that of an ellipse. Moreover, the study by Little and Bagci (1965) established that whenever the major axis is perpendicular to the radial *X* axis of the cylinder, the maximum SCF occurs at both ends of the major and minor axes.

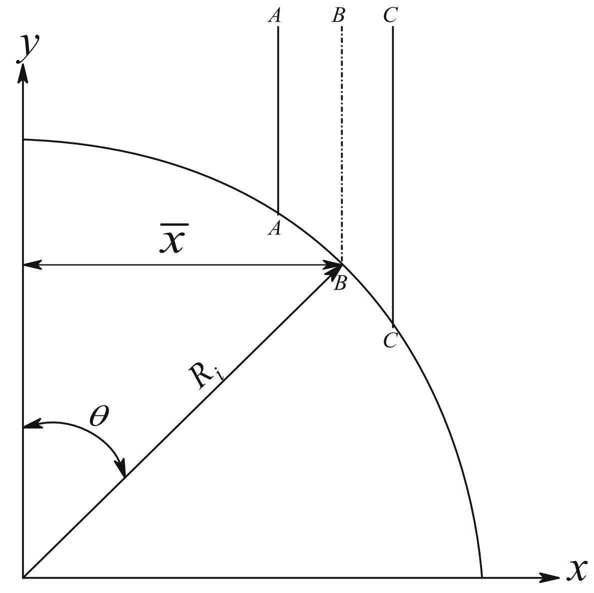

Fig. 1 Configuration of an offset cross bore

Cheng (1978) cited the analytical solution of SCF for a closed-end cylinder at the ends of the major axis as

$$\mathrm{SCF} = \frac{2(\mathrm{C}-1)\mathrm{R}_2^2 + \mathrm{R}_1^2}{\mathrm{R}_2^2 + \mathrm{R}_1^2} \qquad (2)$$

while at the end of minor axis as

$$\mathrm{SCF} = \frac{\left(4R_2^2 \big/ C\right) + R_1^2}{R_2^2 + R_1^2} \qquad (3)$$

where

C—ratio of major and minor axis of the ellipse (ellipticity)

*R*1—cylinder inside radius

*R*2—cylinder outside radius

Comparing the two equations, it was evident that the SCF at the major axis is higher than that of the minor axis.

Further, Cheng (1978) experimentally investigated three different circular cross bore sizes, with size ratios (cross bore to main bore ratio) of 0.05, 0.1, and 0.2 at varying offset locations in a thick cylinder with a thickness ratio of 1.84. The study by Cheng (1978) reported a significant reduction in SCFs due to the offsetting of the cross bore. Masu (1998) studied numerically the effects of offsetting small circular cross bores in a thick-walled cylinder with a thickness ratio of 2. SCF reductions of 17% and 42% were reported, when the cross bore was positioned in an offset ratio of 0.24 and 0.9, respectively, from the radial line. A similar work had been done experimentally by Cole et al. (1976). The findings of the above-cited two authors concurred. A brief comparison of the findings between the two studies is tabulated in Table 1.

Makulsawatudom et al. (2004) studied small circular and elliptical cross bore using finite element analysis. The thickness size of the cylinders was between 1.5 and 2.5. The study investigated the effects of SCFs when the openings were located at the center of the cylinder axis and in a single offset position. The lowest magnitude of SCF occurred in the plain elliptical cross bore located at the center of the cylinder. Further comparison between authors on SCFs at the vessel intersection with cylinder thickness ratio of 2 is shown in Table 2.

Hyder and Asif (2008) also studied stress concentration along the height of the cross-bored cylinder under internal pressure. Stress concentration was investigated at five different segments along the cylinder height from the top. The location of these segments was at $^{1}/_{16}$, $^{1}/_{8}$, $^{2}/_{8}$, $^{3}/_{8}$, and $^{4}/_{8}$ (center of the cylinder). The optimum and maximum SCF occurred at $^{1}/_{8}$ and $^{4}/_{8}$

, respectively.

The SCF at $^{1}/_{16}$ was considerably high due to the effects of the closed ends of the cylinder (Saint Venant's principle). According to this study, for optimum conditions, the cross bore should be positioned away from the cylinder center and its closed ends.

Cross bore obliquity

A configuration illustrating an oblique cross bore is shown in Fig. 2.

It is worth noting that oblique angles of the cross bores are measured either clockwise from transverse plane or counterclockwise from the longitudinal axis of the cylinder as shown in Fig. 2.

The Little and Bagci (1965) study, which had been reviewed in the preceding sections, also reported that small inclined cross bores in the longitudinal plane have their major axis parallel to Z direction. Therefore, maximum SCF in closed thick-walled cylinder occurs only at the ends of the major axis and was given by

$$\mathrm{SCF} = \frac{4CR_2^2 + R_1^2}{R_2^2 + R_1^2} \tag{4}$$

The symbol notations remain the same as those given in Eq. 2.

Nihous, Kinoshita, and Masutani (2008) also studied radial oblique cross bores oriented at five different angles using a numerical method for various cross bore sizes. The oblique angles studied were 30°, 45°, 60°, 75°, and 90°. These oblique angles were measured counterclockwise from the longitudinal axis of the cylinder. Notably, the study reported increased mesh element distortion whenever the obliquity angle was below 30°. In addition, it was observed that, as the oblique angle reduced from 90° to 30°, the SCF magnitude increased significantly.

Thickness ratio

Masu (1991) studied SCFs at the intersection of the cylinder bore and plain circular cross bore, on cylinders with thickness ratios of 1.4 and 2.0. The specimen tested had ratios of cylinder length to outside diameter ≥ 2 and cylinder bore radius to cross bore radius ≥ 7.5. The study reported that SCFs decrease with decreasing thickness ratio. Further, tabulation of some of SCF results obtained at the intersection of the cross bore and main cylinder bore using various techniques with different thickness ratios (K) is shown in Table 3.

The data in Table 3 revealed that the highest and the lowest SCF occurred in the cylinder with a thickness ratio of 3. The highest SCF of 3.78 was obtained by Chaaban and Burns (1986) using 3D FEA while the lowest of 2.51 was reported by Faupel and Harris (1957) using an experimental method, at $K = 3.0$. However, a strict comparison could not be done on these SCFs since they were obtained using various cross bore sizes.

Kihiu (2002) studied cross-bored thick-walled cylinder under internal pressure having thickness ratios ranging from 1.75 to 3. The study reported a constant SCF of 2.753 over the thickness ratios when the cross bore to main bore radius ratio was at 0.2. However, when the ratio of cross bore to main bore was < 0.2, the SCF increased with increasing thickness ratio, whereas when the ratio was > 0.2 the SCF decreased with increasing thickness ratio. These findings suggested the existence

Table 1 SCF obtained by offsetting of a circular cross bore (Cheng, 1978; Masu, 1998)

Author	K	Cross bore size ratio	Offset location ratio		SCF reduction (%)
Cheng (1978)	1.84	0.05	0.317	0.633	16.37
		0.10	0.300	0.600	13.57
		0.20	0.267	0.533	16.8
Masu (1998) and Cole et al. (1976).	2.0	0.064	0	0.24	17
		0.064	0	0.9	42

Table 2 SCF values at the vessel intersection (Makulsawatudom et al., 2004; Masu, 1998)

SCF at the main cylinder bore cross-bore intersection with cylinder thickness ratio of 2								
	Circular radial cross bore		Elliptical radial cross bore		Circular optimally offset (0.112b) cross bore		Elliptical optimally offset (0.112b) cross bore	
Cross bore shape	Plain	Chamfer	Plain	Chamfer	Plain	Chamfer	Plain	Chamfer
Cole et al. (1976)	–	–	1.80	–	1.80 (1.4–1.5 near the outlet plane)	–	–	–
Masu (1998)	2.30	–	1.52	–	1.33	–	–	–
Makulsawatudom et al. (2004), hole size ratio $\frac{R_C}{b} = 0.01$	3.04	3.7	3.0	2.25	3.00	3.55	2.10	2.5
Makulsawatudom et al. (2004), hole size ratio $\frac{R_C}{b} = 0.05$	2.89	3.4	2.00	2.25	2.80	3.3	2.3	2.6

Where

R_C—cross bore radius

b—outer diameter of the cylinder

of a stress transition point which depends on the size of the cross bore. This particular cross bore size where the SCF magnitude was constant was referred to as geometric constant.

In another study, Kihiu, Rading, and Mutuli (2003) developed a 3D FEA computer program to determine the SCF and geometric constants in a thick-walled cylinder with plain cross bore subjected to internal pressure. The study reported that when the thickness ratio was < 1.75, the geometric constant was 0.11 and the SCF was 2.67, whereas when the thickness ratio was > 1.75 the geometric constant was 0.2 and the SCF was 2.734.

Later, Kihiu (2007) studied universal SCF in chamfered cross-bored cylinders with thickness ratios between 2.25 and 3 under internal pressure. The study reported that SCFs increased with decrease of thickness ratio, contradicting the earlier findings by Masu (1991). The study also reported that thick-walled cylinders were more suitable for chamfering than thin-walled cylinders.

From the preceding paragraphs, it is evident that the three studies conducted by Kihiu et al. led to the development of a quick design tool for cross-bored thick-walled cylinders based on the thickness ratio, cross bore size, and shape.

Discussion and summary

Stress determination is normally done using experimental, analytical or numerical methods. Experimental methods are generally expensive due to the cost of equipment, labor and test specimens.

In analytical methods, stress analysis is done using elastic, elastoplastic, or plastic theories. However, the accuracy of the analytical method depends on the assumptions made during the development of the theory. Numerical methods give approximate results that are fairly accurate. They are cheap, are easy to use, and are amendable to simulation. They are mainly used as verification tools of the results obtained from both experimental and analytical methods. However, most of the commercial software's are predesigned with limited provisions for any alterations.

The introduction of cross bores in high-pressure vessels resulted in reduced pressure carrying capacity of up to 60%. The magnitude of SCFs are observed from the review to depend mainly on design parameters such as the angle of inclination, cross bore size, position, shape, and thickness ratio.

Elliptical cross bores located in the transverse plane of the main cylinder gave lower SCFs than when positioned

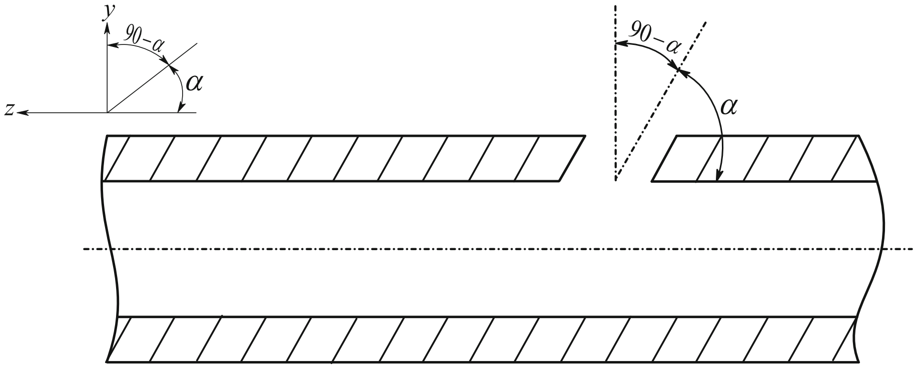

Fig. 2 Configuration of an oblique cross bore

Table 3 Comparison of SCF of radial circular cross bore at the vessel intersection (Makulsawatudom et al., 2004; Masu, 1991)

K	Gerdeen (1972) (photo elasticity)	Fessler and Lewin (1956) (analytical)	Faupel and Harris (1957) (strain gage and photoelasticity 2D & 3D)	Peterson (1974) (strain gage)	Tan and Fenner (1980) (boundary integral element (BIE))	Abdul-Mihsein and Fenner (1983) (BIE)	Masu (1991) (3D FEA)	Chaaban and Burns (1986) (3D FEA)	Makulsawatudom et al. (2004) (3D FEA) hole size ratio $\frac{R_C}{b} = 0.01$	Makulsawatudom et al. (2004) (3D FEA) hole size ratio $\frac{R_C}{b} = 0.05$
1.4	–	2.99	–	–	–	–	2.84	–	–	–
1.5	3.19	3.08	–	–	–	–	–	3.40	2.82	2.73
1.75	–	3.26	–	–	–	–	–	–	2.93	2.83
2.0	3.32	3.4	3.02	3.44	2.98	2.97–3.0	3.03	3.58	3.04	2.89
2.25	–	3.51	2.53	–	–	–	–	–	3.13	2.91
2.5	–	3.59	2.54	–	–	–	–	3.69	3.20	2.94
3	–	3.70	2.51	–	–	–	–	3.78	–	–

in the longitudinal plane. A SCF reduction of up to 33% was noted when an elliptical cross bore in the transverse plane having its major axis perpendicular to the cylinder axis was used, instead of circular cross bore.

Further, positioning elliptically shaped cross bores at the cylinder radial line gave lower SCFs than for a circular one. Offsetting a circular cross bore by an appropriate distance from radial line was found to reduce SCFs, while improving fatigue life by 170%. A maximum reduction of SCF by 42% occurred when the cross bore was positioned at an offset ratio of 0.9 in a thick cylinder with a thickness ratio of 2. However, offsetting an elliptical-shaped cross bore had a slightly higher reduction of the SCF up to 5% than the circular one, despite its high manufacturing cost and drilling difficulties. The optimum position of a cross bore was seen from literature to occur away from the center of cylinder and its closed ends in line with the Saint Venant's principle.

Incorporating chamfers, blends, or radius entry on cross bore, cause stress redistribution that leads to a reduction of SCF. However, cross bores with blended or radiused entry had lower SCFs than those with chamfers, with the plain cross bores having the highest SCFs. Percentage reduction of SCF due to the introduction of chambers in a cross bore was found to depend on the cylinder thickness, cross bore radius, chamfer length, and angle. Using chamfers on cross bores reduced SCFs by a maximum of 34.2% on the main cylinder bore, but introduced other points of peak stress along the cross bore. However, these peak stresses were found to reduce the fatigue life of the cylinders marginally. In addition, chamfers were found to be only suitable for thick-walled cylinders. Notches regardless of their size had an increasing effect on SCFs; hence, they should be avoided in any pressure vessel design.

From the literature reviewed, it is evident that there is no universally known and accepted method for determining optimum stress concentration factors in thick-walled pressure vessels, considering the effects of the combined various geometric design parameters identified. In fact, the existing solutions addressed the optimum conditions based on each design parameter separately, despite most of the parameters being closely interlinked. Other authors compared magnitudes of stress concentrations without taking into consideration the size of the cross bore. In addition, studies carried out so far have failed to determine the optimal conditions in high-pressure vessels with a cross bore under the combination of static, thermal, and dynamic stresses, arising from the geometric configuration, working fluids, at high pressures and temperatures, despite this being a common phenomenon in practice.

Therefore, since high-pressure vessels are designed to operate either under elastic, elastoplastic, or fully plastic conditions, there is a need for further research on optimal geometric configuration of a cross bore with regards to, the cross bore size, location, shape, obliquity, and thickness ratio under these operating conditions.

Conclusion

Stress concentration in high-pressure vessels with a cross bore is affected by the configuration of geometric parameters which include the cross bore size, shape, location, angle of obliquity, and thickness ratio were reviewed in this study. However, the optimization of these geometric parameters has not been established, despite this being a common phenomenon in the industry. The studies which exist only treated each parameter separately, although they never considered the combination of static, thermal, and dynamic stresses, arising from the geometric parameters, working fluids, at high pressures and temperatures. Therefore, a study combining all the above parameters was justified.

Abbreviations

BIE: Boundary integral element; FEA: Finite element analysis; K: Thickness ratio (outer diameter to inner diameter); SCF: Stress concentration factor

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