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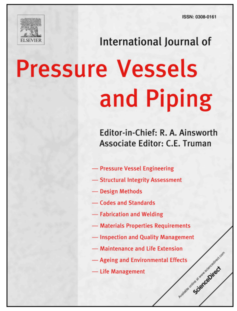

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Parametric Study of Interaction Effect between Closely-Spaced Nozzles in a Thin Cylindrical Pressure Vessel

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Abstract
The presence of nozzle openings in process vessels gives rise to stress concentration due to localization of stresses around openings. Introduction of second nozzle in vicinity of first nozzle will generate its own stress contours and will interact with stress contours of primary nozzle. To investigate the effect of a secondary nozzle, computational simulation has been carried out. The simulation is validated with established benchmarks. Geometry of vessel and nozzle openings, size of reinforcement and other geometric parameters like centre to centre distance, axial distance, etc. affecting maximum stress have been studied. Result for each case is plotted and discussed in detail.

Keywords
Flush-type Nozzle, Stress Concentration, Reinforcement, Interaction Effect, Interacting nozzles

Nomenclature
δ = Distance between two nozzle axes, mm; δ_{ang} = Angular position with respect to axial nozzle plane (on developed surface), degrees; δ_{ax} = Axial distance between two circumferential planes of nozzles, mm; δ_{ctc} = Centre-to-centre distance between two nozzles along the vessel surface, mm; δ_{θ} = Circumferential distance between two axial planes of nozzles, degrees; D = External diameter of pressure vessel, mm; d = External diameter of nozzle opening, mm; dp = Diameter of primary nozzle, mm; ds = Diameter of secondary nozzle, mm; t = Thickness of nozzle wall, mm; T = Thickness of vessel wall, mm; ρ = Radius of curvature of reinforcement, mm; w = Chamfer leg, mm

1. Introduction
The presence of openings in a process vessel gives rise to stress concentration which occurs due to localization of stresses in the process vessel. Knowledge of stress contours around these openings is necessary for safe design of such vessels. To reduce stress concentration, the openings must be properly reinforced. Experimental work on stresses at nozzle connections in pressure vessels has been carried out by Hardenbergh [1] showing the general state of stress at nozzle openings. Photoelastic stress-freezing and slicing method is applied for the study of stresses in a cylindrical pressure vessel with a nozzle by Seika et al [2]. They determined stress distributions on test models made of epoxy resin and established the effect of change in nozzle size and fillet radius. Structural modelling and stress analysis has been performed on nozzle connections in ellipsoidal heads which are subjected to external loading using Timoshenko Shell Theory and finite element method by Skopinsky et al [4]. Reduction of stresses has been achieved in cylindrical pressure vessels using finite element method by Nabhani et al [5]. Stress concentration factors for radial nozzle to spherical shell connection, given in British Standard Specification for unfired fusion-welded pressure vessels, were found out for nozzle-sphere connections by Schindler et al [7] which have been examined and contrasted with current finite element method simulations. Experimental determination of limit and burst pressures for a cylindrical vessel with a *30 deg*-lateral ($d/D>=0.5$), and its comparison with that from the finite element analysis has been carried out by Sang et al [8] where the stress concentration factor, the spread of plastic area and the behavior of deformation are provided.

An introduction of secondary nozzle in the vicinity of primary nozzle will generate its own stress contours and can interact with the stress contours of primary nozzle. Three dimensional photo-elastic