Velocity Field Measurements Using Digital Particle Image Velocimetric System

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Abstract

Particle Image Velocimetry (PIV) is a non-intrusive technique for simultaneously measuring the velocities at many points in a fluid flow. Several case studies related to nuclear reactor were performed with the PIV system. Some of the cases like flow in circular tube, submerged jet, natural convection in a water pool and Fluidic Flow Control Device (FFCD) used in advanced accumulator of Emergency Core Cooling System (ECCS) have been studied using PIV system. Theoretical studies have been performed and comparisons with PIV results are also given in this article.

Introduction

Most innovative nuclear reactor systems under development are single-phase systems. Present day Computational Fluid Dynamics (CFD) codes are considered to be robust for single-phase systems and hence increasing application of these codes is expected for such reactors. However, verification and validation of CFD codes for reactor systems and components is not adequate. For verification and validation of CFD codes, one must be able to measure the multi-dimensional velocity, temperature and concentration fields. Simple experimental techniques are intrusive in nature and make measurements at few selected points only. In the past decade or so, techniques for practically non-intrusive measurement of the field variables have become possible, thanks to successful development of Particle Image Velocimetry (PIV), Planar Laser-Induced Fluorescence (PLIF), etc. A 2D PIV facility has been set-up for flow mapping in BARC. Such a facility plays important role in basic research, design optimisation, (CFD) code development and validation. Flow in circular tube, submerged jet, natural convection in a water pool and fluidic flow control device (FFCD) used in advanced accumulator of Emergency Core Cooling System (ECCS) have been studied using PIV system. Theoretical analysis has also been performed. This article deals with the experimental setups, results obtained by using PIV. The theoretical analysis performed has been compared with results obtained with the PIV system.

PIV system

Particle Image Velocimetry (PIV) is a non-intrusive optical technique for the measurement of flow velocity at many points (typically at thousands of locations) in a flow field simultaneously. It measures instantaneous vector field and displays velocity vectors in real-time [1]. The PIV system used is comprised of Nd:YAG laser source, CCD (Charged Coupled Device) camera, synchronizer (timing controller to control the laser and camera) and analysis software. The setup is shown in Fig. 1. Laser has very short pulse duration (—5-7 ns), which can freeze any motion. To synchronize the laser source and camera, a synchronizer is provided. The flow
measurement technique involves seeding the flow field with tracer particles, illuminating the region under the investigation and capturing two images in rapid succession. Velocity vectors are obtained from the displacement of tracer particles in the time interval between two images captured [2]. For the experiments, glass hollow spheres having density of 1.1 g/cm³ (close to water) and size of 10 μm are used as tracer particles. 2D PIV system can be used to calculate various derived parameters like vector length, vector components, two dimensional divergence, two dimensional vorticity, swirling strength, shear strength, strain, strain rate etc.

Figs. 2b (i) and (ii) show the velocity profile for flow rate of 0.4 lpm and 30 lpm respectively at different axial locations. The Reynolds numbers calculated for these flow rates are 480 and 36000 respectively. It can be seen from the Fig. 2b that measurement taken by PIV system gives parabolic velocity profile for laminar region and flat velocity profile for turbulent region. Figs. 2c (i) and (ii) depict comparison of measured non-dimensionalised axial velocities as a function of non-dimensionalised radial distance with the computed by CFD. The axial locations at which these profiles are shown are at a distance of 13D and 6.25D from inlet for laminar and turbulent flow respectively, where D is inner diameter of the circular tube.

**Flow in circular tube**

The test facility consists of a test section, pump, rotameter and sump. The test section is comprised of a glass tube having inner diameter of 22 mm and a square glass enclosure around the glass tube filled with water. The purpose of water filled square glass enclosure is to minimise the image distortion from the curved surface of pipe. Test section used is shown in Fig. 2a. Experiments were carried out for different flow rates. Flow in a circular tube, submerged jet, natural convection in a water pool and fluidic flow control device (FFCD) used in advanced accumulator of Emergency Core Cooling System (ECCS) have been studied using PIV system. The various experimental setups and results for each are described in following sections.

**Flow pattern studies**

Flow in a circular tube, submerged jet, natural convection in a water pool and fluidic flow control device (FFCD) used in advanced accumulator of Emergency Core Cooling System (ECCS) have been studied using PIV system. The various experimental setups and results for each are described in following sections.
**Submerged water jet**

In the secondary shutdown system of Pressurised Heavy Water Reactor (PHWR) and Advanced Heavy Water Reactor (AHWR), liquid poison is injected into moderator in Calandria vessel through perforated tubes to shutdown the reactor. Poison coming out from the perforated tubes is in the form of submerged jets. It is important to know the velocity pattern of submerged jet in presence of calandria tubes. As a first step, single submerged jet without any obstacles is studied using PIV. Experiments are performed on the submerged jet issuing from a tube of inner diameter of 6.5 mm. Fig. 3a shows the test setup which comprises of water tank with circular tube. Fig. 3b shows the velocity pattern obtained by using PIV system. Fig. 3c shows the variation of axial velocity as a function of axial length. Comparison of PIV measurement with CFD and analytical [3] results is shown in Fig. 3c. Fig. 3d shows the velocity contours of jet obtained by PIV system.
In advanced nuclear reactors, large water pools have been employed for removal of core decay heat passively during reactor shut down. Heat exchangers connected to primary circuit are immersed in these pools. The heat exchanger transfers heat from primary circuit to water pool by buoyancy driven natural convection phenomena. During heat transfer process, thermal stratification with a steep temperature gradient along the vertical plane occurs in the water pool.

Natural convection flow pattern in water pool due to vertical plate heater is studied using PIV system. The experimental setup consists of vertical heater plate immersed in a water tank as shown in Fig. 4a. The heater plate was given electrical power of 313 W. As the plate is heated, boundary layer flow develops adjacent to the plate. PIV measurements for flow pattern are taken after 15 s of switching on the heater. CFD analysis has been also carried out to compare with experimental data.

Figs. 4b and 4c show the flow pattern obtained by using PIV system and aluminium particles respectively. Both flow patterns match closely. It can be further observed from Figs. 4b and 4c that fluid moves up along the vertical heater to the free surface. At the free surface, the detaching boundary layer is reflected downwards. However, due to its higher temperature (lower density), it is found to rise back to the free surface and flows along the free surface horizontally towards the wall of the container. Comparison of resultant velocities from PIV and CFD results as a function of distance from vertical heater is given in Figs. 4d and 4e for 5 mm and 50 mm below free surface respectively.

**Fluidic Flow Control Device**

Emergency Core Cooling System (ECCS) is provided to limit the fuel temperature rise within acceptable
The advanced accumulators in advanced heavy water reactor inject large amount of cold water by passive means, at high pressure, directly into the core for short period of time and then a relatively small amount of cold water for large period of time to quench the core. For this, it was proposed to incorporate a Fluidic Flow Control Device (FFCD) at the bottom of accumulator tank as shown in Fig. 5a, which reduces the flow after some time, by passive means. This feature enables to extend the accumulator discharge. During initial period, the water level in the advanced accumulators is above the stand pipe, the water enters the vortex chamber of the FFCD through both stand pipe (radial) and side connection (tangential) as shown in Fig. 5b (i), and after some time when the water level in the accumulators falls below the top of the stand pipe, the water enters the chamber through the side pipe only, which is tangential to the vortex chamber as shown in Fig. 5b (ii). This causes the formation of vortex, which increases the flow resistance, and hence reduces the flow rate passively.

For PIV experiment, FFCD was made of glass. Only the side pipe and outlet are considered for study the vortex in FFCD as vortex study is of our interest. The experiments were conducted for various flow rates. Circular mid plane is studied using the PIV system for velocity pattern and Fig. 5c shows the stream line plot generated by PIV software. Fig. 5d shows the variation of non dimensional tangential velocity with non-dimensional radius using PIV.
system. Results show that tangential velocity increases to peak value with radius then decreases.

Fig. 5c: Velocity stream line and contour using PIV system

Fig. 5d: Tangential velocity distribution using PIV system

The tangential velocity profile obtained is similar to profile obtained from empirical correlation proposed by Vatistas et al. [4].

Concluding Remarks
Flow pattern studies have been carried out for various geometries pertaining to nuclear reactor systems. Further work on computational fluid dynamics studies for these components/systems are in progress for comparison purpose. Up-gradation of 2D PIV system to 3D PIV and procurement of additional components for two phase flow measurement are in progress.

Reference