many researchers in experimentation such as Schwartz and Smith [3], J. Price [5].

6. Pitot-Static Tube

These are the simplest and cheapest method available to measure velocity at a point. These are best suited for finding the mean velocity in fluids of constant density. Probe blockage of the flow is not a problem in large ducts and away from walls. They are subject to mean flow misalignment errors. They are frequently used in the field and laboratory alike.

7. Magnetic Resonance Imaging (MRI)

This technique is used to determine the pore structure and internal velocity distribution in packed bed. In this technique magnetic susceptible fluid is used. And this fluid is then passes through packed bed. The fluid flowing is mixed with doping material to reduce the measurement time. To get the image of fluid flow the velocity of flowing fluid is generally kept low and the image of flow structure is taken by high CCD camera. The MRI technique is used by Ogava et al. [8], and Mantle et al. [9].

8. Nuclear Magnetic Resonance (NMR)

This technique is used to measure the internal velocity within packed bed. The bed is retained in stainless steel grid of suitable mesh size. The fluid flowing is doped with magnetic material and low flow rate is used. This technique shows the output in terms of the graph which can be interpreted. The NMR technique is used by Lebon et al. [10].

9. Laser Doppler Anemometry (LDA)

The Doppler Effect describes the phenomenon experienced by an observer whereby the frequency of light or sound waves emitted from a source that is traveling away from or toward the observer is shifted from its original value and by an amount proportional to its speed. When a laser beam is used as the incident wave source, the velocity measuring device is called a laser Doppler anemometer (LDA). LDA measures the time-dependent velocity at a point in the flow. A laser beam provides a ready emission source that is monochromatic and remains coherent over long distances. It is a relatively expensive and technically advanced point velocity measuring technique that can be used for most types of flows but is also well suited to hostile, combusting, or highly dynamic (unsteady, pulsatile, or highly turbulent) flow environments. It offers good frequency response, small spatial resolution, no probe blockage, and simple signal interpretation, but requires optical access and the presence of scattering particles. This method provides very good temporal resolution for time-accurate measurements in turbulent flows.

A high pulsed laser beam is impinges on the fluid flowing through packed bed. This fluid used is generally doped with doping material (or tracing particle) to match with the refractive index of glass. The packing material is made of high quality to reduce the scattering of laser beam due to impurities. And this scatter image is taken by high resolution camera. LDA technique is used by Giese et al. [13].

10. Particle Image Velocimetry (PIV)

Particle Image Velocimetry (PIV) measures the full-field instantaneous velocities in a planar cross section of a flow. The technique tracks the time displacement of particles, which are assumed to follow the flow. The image of particles suspended in the flow are illuminated and recorded during very-short-duration repetitive flashes of a laser beam. These images are recorded and compared. The distance traveled by any particle during the period between flashes is a measure of its velocity. By repeatedly flashing the laser, in the manner of a strobe light, the particle positions can be tracked and velocity as a function of time obtained. This technique works in gases or liquids. The particle size and properties should be chosen relative to the fluid and flow velocities expected so that the particles move with the fluid, but large enough relative to camera pixel size to avoid peak-locking errors. The PIV technique is used by Tchikango et al. [14], and Yuki et al. [15].

11. Electrical Resistance Tomography (ERT)

Electrical Resistance Tomography (ERT) is a measurement technique for obtaining information about the contents of process column, vessels and pipelines. Multiple electrodes are arranged around the boundary of the vessel at fixed locations in such a way that they make electrical contact with the fluid inside the vessel but do not affect the flow or movement of materials. The basic principle of ERT is to install a number of sensors around the pipe or vessel to be imaged. This reveals information on the nature and distribution of components within the sensing zone. The sensor output signals depend on the position of the component boundaries within their sensing zones. The ERT technique is used by Doan et al. [17] and N. Aoda [16].

The constraints involved with the use of MRI and NMR measurements techniques are that it is limited to non-magnetic and non-metallic materials. Also the cost involved in acquiring this instrumentation requires large financial investments. LDA and PIV require transparent test sections and careful refractive index matching between the bed and the fluid being used in order to measure the interstitial velocities inside the bed while the hot wire anemometer and pitot tube are cheap and easily available.
The investigation of velocity distribution within fixed bed can be done by experimental investigation and by mathematical modeling.

12. Velocity Measurement By Intrusive Measurement Techniques

Arthur et al. [1] investigated radial velocity distribution of air through fixed bed of charcoal granules having size 9 to 28mm in a glass tube of 48.3mm diameter. The flow rate was measured by using soap bubble techniques. In this technique, air flow rate is measured by allowing the flow to drive a soap bubble along a tube and observing the time taken by bubble to sweep out a calibrated volume. According to them, fluid flow is not uniform across a fixed bed. Their experiment does not give point velocities but indicated that fluid velocity is maximum near the wall of tube and minimum at centre of the tube. According to them, the main factor affecting the flow rate distribution is bed porosity.

Morales et al. [2] employed a series of circular hot-wire anemometer of different diameters to measure fluid velocity at radial positions of bed. In their measurement, air velocity varied between 0.123 to 0.533 m/s by using three pellets of diameter 3.175, 6.35 and 9.525mm in a tube of 52.5 mm diameter. The results obtained shows that velocity distribution in fixed bed is a function of air velocity and bed height. According to them, two factors are responsible for velocity distribution i.e. skin friction at tube wall and variation in void space in bed with radial position. The authors also remarked that velocity distribution is not dependent of the distance of the anemometer above the top of the bed.

Schwartz and Smith [3] investigated the velocity distribution at downstream of cylindrical fixed bed using five circular hot-wire anemometer at various radial position. Data were obtained by using spherical and cylindrical pellet of diameters 3.175, 6.35, 9.525 and 12.7mm over a range of pipe diameter to pellet diameter (D/D_p) from 5 to 32. The three different size of tube used having 50.8, 76.2 and 101.6mm diameter. The length of cylindrical pellet was equal to diameter. They also investigated that the effect of distance between the exit of bed and the plane of measurement on the measured velocity profile. They assumed the ratio of point velocity to average velocity equal to 1 at r/R equal to 0.55. By assuming this, they concluded that, in their system a distance of 50.8 mm between the bed and the anemometer would minimise the error. According to them, the maximum or peak velocity ranges up to 100% higher than the centre velocity as ratio of D/D_p decreases. When $D/D_p > 30$ then, divergence of velocity profile from assumption of uniform velocity is less than 20% and for $D/D_p < 30$, it is 30% to 100%. The maximum peak velocity profile occurred at a distance of approximately one particle diameter from the wall, regardless of pipe and packing size.

Cairns and Prausnitz [4] measured velocity profile inside bed. They used electrode techniques to measure mean axial velocities over a length of bed, using both fixed and fluidized bed with water as a fluid. A salt tracer solution was injected into the main stream over entire cross section of bed and time interval necessary to detect sudden change in rate of injection at zero position was measured at downstream. Electrical conductivity cells detect changes in injection rate at radial and axial positions. The pipe diameter used having diameter 50.8 mm and sphere diameter 3.2 mm. The velocity was found to be flat apart from the slight high at centre of tube. According to them, there is limitation in generating velocity profile near the wall by employing material balance. This is due to the value of local bed porosity is assumed constant over the cross section of bed.

J. Price [5] measured fluid velocity distribution for a number of randomly packed beds of spheres having 0.635, 1.27 and 2.54 mm diameter with 3.8 mm diameter pitot - static tube at the exit of fixed bed. The test bed having 30.4 mm diameter contained between 5 mesh screens and honeycomb was located on its exit face. The bed length was varied between 11.43 to 45.72 mm. The honeycomb consisted of annular rings joined together by radial vanes. The result obtained was, the velocity distribution independent of Reynolds number ($1470 < Re < 4350$) and bed length ($9 < L/D_b < 36$) and the sphere material over the range tested. It is slightly affected by packing method, sphere properties and tube to ball diameter ($12 < D/D_b < 48$). The maximum velocity was found to exit within one-half sphere diameter from the walls of containing tube.

Newell and Standish [6] used thermistor anemometer to measure velocity distribution of gas in fixed bed using square and rectangular duct. The air velocities determined are 0.04, 0.08 and 0.09 m/s. Their result states that, the fluid flow in square and rectangular fixed bed is similar to circular bed. Their measurement also indicated that fluid velocity reached maximum at less than one particle diameter from the wall.

Ziolkowska and Ziolkowski [7] used thermo anemometric technique to measure velocity distribution at the exit of gas flow in fixed bed. They used random packing with tube diameter 94 mm and bed height 1050 mm with spherical particle diameter between 4.11 to 8.70 mm. The range of superficial velocity was 0.4 to 1 m/s. They found that, with an accuracy of ± 3.2 %, the shape of local gas velocity radial profile does not depend on flow rate. The pellet diameter had a more pronounced effect than the flow rate on the shape of velocity profile. If pallet diameter is smaller, then velocity profile will be flatter.

13. Velocity Measurement by Non-Intrusive Measurement Techniques

Ogawa et al. [8] made use of MRI technique to measure the pore structure and internal three dimensional velocity distributions in fixed bed. He used 38mm cylindrical bed diameter filled with crush glass particles ranging from 2 to 5 mm and spherical glass bed of 5 mm diameter. Fluid was doped with copper sulphate. Flow velocity ranging from 0.00384 to 0.0132 m/s and Reynolds number for crushed glass was 10, 25 and 40 and for spherical glass are 19.3. From their velocity map, region near wall with higher velocity factor can be observed, indicating presence of wall channelling.

Mantle et al. [9] used a hollow gas flow column 40mm inside diameter and 500 mm height, packed with different size of pellet having 1.3, 3 and 1.6 mm diameter and got three dimensional flow visualization. A plot of average fluid velocity plotted as a function of distance from the column wall. According to them, velocity is maximum porosity at wall. The local velocity is clearly affected by pore space and velocity is enhanced within a distance of one particle radius of column wall.

Lebon et al. [10] used NMR to investigate internal velocity distribution of cylindrical fixed bed of glass. The bed has inside diameter 80 mm and bed diameter 800 ± 150 µm. The packing depth was 100 mm and flow rate ranges from 1.5 to 7.3 ml/min. This flow rate corresponds to interstitial velocities of 0.0013 to 0.0067 m/s and Reynolds number of

0.36 to 1.8. They have not provided velocity profile but shows graph representing velocity probability distribution.

Stephenson and Stewert [11] employed optical measurement technique to measure velocity and porosity distribution inside bed. The experiments were done in vertical 75.5 mm diameter fused quartz tube, randomly packed for length of 145 mm with cylinder cut from fused quartz rod. They used tetra-ethylene glycol, tetra-hydropyran-2-methanol and a mixture of cyclo-octane and cyclo-cetane as a fluid in order to fulfil the requirement of range of Reynolds number and Newtonian fluid characteristics. The velocity has peak near a wall, where porosity is largest and its fluctuations corresponds to those local porosity. McGreavy et al. [12] supported the above result by experimental work by using LDA. With the help of LDA, they measured the velocity distribution inside and at exit of bed.

Giese et al. [13] employed LDA to measure velocity distribution inside a cylindrical fixed bed with spheres, deformed spheres, cylinder and raschig rings. The cylinder has inside diameter 80 mm mounted on high precision table, which can be moved in three directions with an accuracy of ± 0.025 mm via computer. The liquid used was a mixture of 95% dibutylphtalat and 5% ethyl alcohol. The sphere diameter used is 8.6 mm and Reynolds number ranging from 4 to 532. The obtained velocity profile clearly indicates that presence of wall channeling and also damped oscillatory trend in accordance with porosity distribution. The velocity increase at low Reynolds number (Re = 4) and as Re increases the peak velocity decreases. From their result, maximum measured superficial velocity is approximately 3.75 times more than the average superficial velocity through empty cylinder.

Tchikango et al. [14] used PIV to measure velocity distribution in the flow through void space between randomly packed spheres. The test section contains randomly placed spheres confined by cylindrical tube with 500 mm inner diameter. Two different sphere diameter 9 and 30 mm used. The fluid is naphten basic medical white oil (Shell Odina 927) with fluorescent tracer particle (Rhodamin coated particle with 10nm diameter). The volumetric flux is 0.2 ltr/s corresponds to Reynolds number equal to 15 and 45. They concluded that, velocity in tube filled with small sphere is higher as in tube filled with big spheres because of channelling effect of due to lower porosity.

Yuki et al. [15] applied PIV visualization to identify the complex flow structure in sphere packed pipe by using sodium-iodide solution as a working fluid. They used acrylic cylinder 30mm diameter with Na-I solution at 30^0C. A 2-D flow structure is quantitatively visualized from the movement of tracer particle. The tracer particle used was fluorescent resign particle with 1-20 µm diameters. The maximum flow rate under sphere unpacked condition used is 200 ltr/min. The test section consists of pipe of 56 mm inside diameter and 670 mm length. The visualization area is located at 8.2D (460mm) downstream from inlet of test section. The flow field conducted at three Reynolds numbers of 800, 2000 and 4900. They observed that, high velocity spouting flow observed around the tube due to wall effect of low spouting flow from central area.

Aoda N [16] applied ERT to visualize flow pattern and liquid distribution in randomly fixed bed. The diameter of packed column was 300mm and 1500 mm bed height filled with 20 mm plastic spheres. Experiments were performed at low flow rate of 0.0027, 0.0054 and 0.008 m/s. He observed that velocity near column wall was not uniform which supports the experimental observations done by Arthur et al. [1], Schwartz and Smith [3], Newell and Standish [6]. The deviation caused due to oscillation pattern of voidage through fixed bed, resulting flow travelling at different velocity through fixed bed. According to author, there is an increase in the contact area between the probe and stagnant liquid that results in different causing varied local velocities.

Doan et al. [17] applied ERT to measure liquid distribution and velocity at various axial distances. They used 300 mm diameter column filled with 20mm polypropylene spheres. The fixed bed height was 6 times column diameter. The electrodes were installed flush with the inside wall of the column. A 0.5% wt salt solution (Conductivity = 9.95 ms/cm) was used as a high conductivity tracer and liquid flow rate ranging from 8.83 to 0.00126 m^3/s. They observed that in upper flow, the liquid follows plug flow pattern and was not distorted by liquid hold up and liquid channelling. The liquid distribution factor decreases with bed height and liquid flow rates.

14. Conclusion

From the above, it can be concluded that velocity profile is not uniform across fixed bed. The velocity distribution through a fixed bed strongly depends on bed geometries and fluid flow conditions. The maximum value of velocity occurs near the wall. This is due to opposing effect of wall and variation in bed porosity with radial positions of the wall i.e. due to (D/D_p). The velocity distribution inside fixed bed is also dependent on Reynolds number for Re<500. For higher Reynolds number Re>500, the dependency of velocity profile on it no longer exists and profile remains constant. Thus according to the fluid flow, it is fully developed flow before entering in fixed bed and after exit from the fixed bed. But in transition phase of fluid flow it is important to know the velocity profile within fixed bed. The non-intrusive measurement techniques are most suitable for such experimentation though their cost is high. But these measurements can predict the accurate pattern of flow within the fixed bed.

15. Nomenclature

d	Radial distance
D	Column diameter
D_b	Ball diameter
D_p	Particle diameter
r	Radial position
R	Column radius
Re	Reynolds Number

References

[1] Arthur, J. R. Linnett, J. W.Raynor, E. J. and Sington, E. P. C., “The flow of an air stream through a layer of granules”, Trans. Faraday Soc., 46,pp270-281, 1950.
[2] Morales, M. Spinn, C. W. and Smith, J. M., “Velocities and thermal conductivities in packed beds”, Ind. Engg. Chem. Res., 43, pp225-232, 1951.
[3] Schwartz, C. E. and Smith, J. M., “Flow distribution in packed beds”, Ind. Engg. Chem., 45, pp1205-1218, 1953.
[4] Cairns, E. J. and Prausnitz, J. M., “Velocity profiles in fluidized beds,” Ind. Engg. Chem., 51, 12, pp1441–1444, 1959.
[5] Price, J., “The distribution of fluid velocities for randomly packed beds of spheres” Mechanical & Chemical engineering Transactions, 1, 7 May, pp7-14, 1968.
[6] Newell, R. and Standish, N., “Velocity distribution in rectangular packed beds and non-ferrous blast furnaces”, Metall. Trans., 4, pp1851, 1973.
[7] Ziolkowska, I. &Ziolkowski, D., “Modelling of gas interstitial velocity radial distribution over a cross-section of a tube packed with a granular catalyst bed”, Chemical Engineering Science, 48(18) Jan, pp3283-3292, 1993.
[8] Ogawa, K., Matsuka, T., Hirai, S. & Okazaki, K., “Three-dimensional velocity measurement of complex-saturated porous media by the tagging method in the MRI technique”, Measurement Science and Technology, Nov, 12, pp172-180, 2001.
[9] Mantle, M. D., Sederman, A. J. & Gladden, L. F., “Single and two phase flow in fixed bed reactors: MRI flow visualization and lattice boltmann simulations”. Chem. Engg. Sci., 56, pp523 – 529, 2001.
[10] Lebon, L., Oger, J., Leblond, J., Hulin, J. P., Matrya, N. S. & Schwartz, L. M., “Pulsed gradient NMR measurements and numerical simulation of flow velocity distribution in sphere packing”. Physics of Fluids, 8, Feb., pp293-301, 1996.
[11] Stephenson, J. L. and Stewart, W. E., “Optical measurements of porosity and fluid motion in packed beds”, Chem. Engg. Sci., 41, pp2161–2170, 1986.
[12] McGreavy, C., Foumeny, E. A. & Javed, K. H., “Characterization of transport properties of for fixed beds in terms of local bed structure and flow distribution”, Chem. Engg. Sci., 41, pp787 – 797, 1986.
[13] Gies, M., Rottschafer, K. & Vortmeyer, D., “Measured and modeled superficial flow profiles in packed bed with liquid flow”, The American Institute of Chemical Engineers Journal, 44, Feb., pp484- 490, 1998.
[14] Tchiknago, A. S., Knieke, C. & Brenner, G., “Measurements of flows in randomly packed beds using the particle image velocimetry”. Proceedings 13th Int. Symp. On Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal 2006.
[15] Yuki, K., Okumura, M., Hashizume, H. and Toda, S., “Flow Visualization and Heat Transfer Characteristics for Sphere-Packed Pipes”, Journal of Thermo physics and Heat transfer, 4, 22, 2008.
[16] Aoda, N., "Visualization of flow pattern and measurement of liquid distribution in a random packed column using electrical resistance tomography (ERT)" (2010). http://digitalcommons.ryerson.ca/dissertations/665
[17] Doan, H. D. and Lohi, A., “Measurement of Liquid Velocity and Liquid Distribution in a Packed Bed Using Electrical Resistance Tomography” Mass Transfer - Advanced Aspects, pp729-742, 2010.