An Improved Sparge Pipe Air Distribution System for a Fluidised Bed Combustor

D R Garwood, J Ward, D R Bowen, M Fisher, and D Gent

ABSTRACT

The purpose of the air distribution system in a fluidised bed combustor is to provide a reasonably uniform spread of combustion air over the entire horizontal cross-sectional area of the bed. One of the simplest, and hence cheapest, forms of air distributor is the sparge pipe design, in which an array of horizontal pipes is fitted at the base of the bed. Combustion air is then supplied to one end of each pipe and is subsequently distributed to the bed through a series of downward facing holes. The paper describes the development of an improved sparge pipe system for a large coal fired fluidised bed producing hot combustion gases for drying of pressed sugar beet pulp. The air flow out of the holes varied by a factor of three along the length of the pipes with the existing system and in addition the overall flow and hence the thermal output of the bed was unduly restricted. Excessive erosion of the pipe walls near some of the holes was also a problem.

A computational fluid dynamics (CFD) study was undertaken of the flows along the pipes using FLUENT and the results validated by flow and pressure measurements on full scale laboratory models. The flow distribution was substantially improved and the overall flow rate increased by approximately 9% by varying the hole diameters and pitches. Wear tests were also undertaken in near ambient temperature fluidised beds using multiple thin layers of different coloured paints on the outside of the pipes to assess the erosion patterns. These patterns were found to be similar to those observed on actual sparge pipes removed from the combustor at the end of an operating campaign. The rate of wear can be substantially reduced by reducing the angle of inclination of the downward facing holes in the pipes. Consequently an improved sparge pipe air distributor was designed for this large fluidised bed combustor.

1. INTRODUCTION

Fluidised bed combustors have been applied in boilers and hot gas producers since they are capable of efficiently burning a wide range of fuels. A common feature of all fluidised bed combustors is the need for a distributor to provide a substantially even distribution of combustion air across the entire horizontal cross-sectional area of the bed whilst resisting the "run-back" of bed particles. Consequently many distributor arrangements have been employed, over the years, including porous ceramic plates to more common forms of metal construction. Metal distributors have operated uncooled (apart from the flow of combustion air), but have also been water-or air-cooled in higher temperature applications. They usually consist of porous or perforated plates or a variety of upriser tubes or standpipes mounted above plenum boxes. However one of the simplest, and hence cheapest forms of air distributor is the so-called sparge pipe system in which an array of horizontal pipes is fitted at the base of the bed, see Fig. 1. Combustion air can then be supplied from one or more plenums to one end of each of the pipes before being fed into the bed through a series downward facing holes distributed along the along the length of the pipe.

These sparge pipe systems can experience problems in practice. Thermal distortion can often occur due to non-uniform heat transfer and temperature gradients around the pipe and it can be difficult to achieve a substantially uniform air distribution along the length of the system. An incorrect design can lead to excessive air flow from some of the holes and hence high localised bed particle turbulence, which can subsequently result in erosion of the pipe wall. This in turn can make it necessary to prematurely replace individual sparge pipes with a consequent increase in maintenance costs and reduction in plant availability. Conversely, if parts of the bed experience air flows which are inadequate for all operating conditions, there is a risk of 'clinkering' and bed defluidisation. Moreover depending upon exit hole diameter and geometry and sparge pipe wall thickness, it appears that bed particles can be entrained into some of the holes in these low velocity regions. This results in deposition of sand particles inside the sparge pipes and consequent exacerbation of pipe-wall temperature gradients and hence enhanced problems of distortion.

This paper is therefore concerned with improving the design of a sparge pipe air distributor installed in a large coal-fired fluidised bed which is operated by British Sugar to produce hot exhaust gases for subsequent drying of pressed sugar beet pulp. The area of the bed is sub-divided into four combustion 'zones' each containing 17 sparge pipes and can be fluidised by either fresh air or a mixture of air and the exhaust gases recycled from a heavy fuel oil fired boiler. The high pressure drops in the sparge pipes restrict the rate of flow of fluidising gases and this, together with the

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Fig 1. *Sparge Pipe Distributor in a Fluidised Bed*

need to maintain acceptable bed temperatures, limits the maximum rate of coal burn. Therefore the fluidised bed operates at a thermal output significantly below its nominal value of 40.6 MW so that one objective of the work was to attempt to increase this flow rate whilst achieving an acceptable flow distribution along the pipe length.

Poor distributor design can be a major cause of operating problems in fluidised beds, [1], so that various systems have been adopted, [2]. Moreover the flow characteristics of distributors have received considerable attention in previous publications, see for example [1]–[6]. These studies have mainly been concerned with perforated plate or porous plate type systems and in these situations relatively uniform bed flows can be achieved by ensuring that the flow resistance across the distributor is relatively large compared to that of the bed, [7]. The flow characteristics of sparge pipes are significantly different and there does not appear to have been previously published information on flow distributions in these distributors. Consequently a computational fluid dynamics (CFD) study was undertaken of the flow characteristics of alternative designs of sparge pipes as part of the present project and the results validated by flow and pressure laboratory measurements on full scale pipes.

The current design of sparge pipe also suffers from erosion of the pipe wall and elongation of some of the holes. Erosion of tubes immersed in a fluidised bed has long been recognised as an operating problem so that it has been the subject of extensive study, see for example [8]-[11]. These studies have largely been concerned with wear of "in-bed" tubes so that the effects of bed hydrodynamics and tube geometry cannot be applied directly to sparge pipes. Consequently erosion of the distributor was studied in a near ambient temperature fluidised bed using pipes coated with a multi-layer paint technique. This produced wear patterns which were similar to those obtained in practice on the full-size plant.

2. FLOW CHARACTERISTICS OF THE SPARGE PIPE DISTRIBUTORS

This aspect of the project involved a computational fluid dynamics (CFD) simulation of the flows of combustion air through the current sparge pipe as well as through pipes with alternative hole arrangements using FLUENT, a commercial computer code**.**

2.1. Flow Distribution in the Existing Sparge Pipes

The existing sparge pipes have an external diameter of 88.9mm and a wall thickness of 7.62 mm with 55 holes along each side of the pipe. The diameter of these holes was 10 mm and they were spaced uniformly at a pitch of 30 mm along the length of the pipe and inclined downwards at an angle of 35º from the horizontal. Pressure boundary conditions were employed in the simulations at the pipe entry (the measured inlet plenum pressure on the plant) and exit from the holes (the bed back pressure). A series of grid independence studies were undertaken to develop an appropriate computational grid and the final grid contained a total of approximately 180,000 cells with a fine mesh near and within the holes. The predictions for the existing pipe were validated by comparison with laboratory pressure and flow measurements along the length of a full scale perspex model. The measurements and predictions were in good agreement with a maximum difference in mean velocities of approximately 1.5% whilst the static pressures differed by less than 2%.

The predictions for this existing sparge pipe indicate that there is likely to be considerable maldistribution in the air flow through the fluidised bed since the flow rates per unit horizontal bed area associated with each pair of holes (i.e. the flow rate out of the two holes either side of the pipe divided by the product of the hole pitch and the lateral pipe centre to centre spacing) vary by approximately 3.5:1 along the length of the pipe, see Fig. 2. In this case the hole pitch is uniform so that the flow distribution also represents the relative distribution of air flow through each hole. It is clear that very high flows ensue through the holes at the far end of the sparge pipe with much lower flows at the "entry" end with an overall flow rate through the system of 0.345 kg/s.

The low flow rates in the entry end holes of the pipe result from a large area of re-circulating flow which

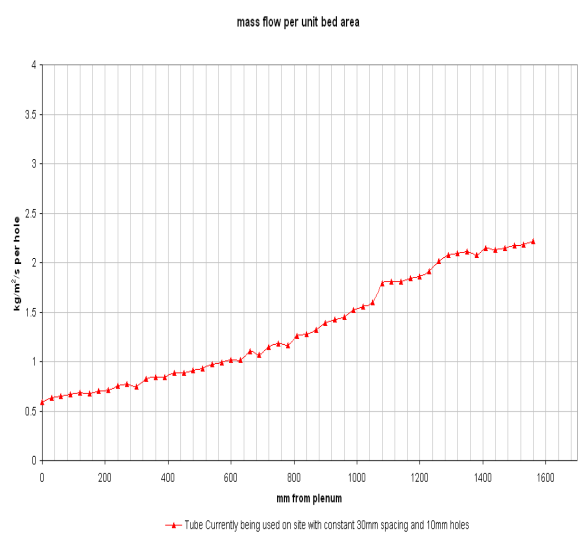

Fig. 2. Flow Distribution in the Fluidised Bed for the Existing Pipe

exists within these holes, see Fig. 3 which presents a plot of the velocity vectors exiting the hole. This recirculation which is a result of the high flow momentum in the sparge pipe at this location obstructs the flow out of the holes and effectively “blocks” a substantial part of the cross-sectional area of the holes. Moreover bed sand particles which are drawn into this re-circulating flow can be subsequently re-entrained into the relatively high velocity flow leaving the hole and this is a possible cause of the elongation of the holes and pipe erosion which are often observed in practice at this end of the pipe. Re-circulation of the flow is not predicted in the holes near the far end of the pipe, see Fig. 4. However the high flow rates leaving these holes and the associated high velocities may well generate high levels of turbulence and recirculation in the bed near the exit of the holes and this may subsequently result in the pipe erosion which often occurs in this region.

2.2 Flow Distributions in Improved Sparge Pipe Designs

In an attempt to reduce the flow maldistribution, and increase the overall flow rate of air, CFD simulations were undertaken for a sparge pipes incorporating a wide range of different hole geometries in which both the diameter and pitch between holes were varied along the length of the pipe. The geometries studied in these simulations gradually evolved to yield an improved design (so-called sparge pipe A) which provided a more uniform flow through the fluidised bed. The predicted flow rates for this sparge pipe which incorporated eight 13 mm diameter holes per side at the entry end of the pipe followed by four 12 mm diameter holes per side and then five 11 mm diameter holes per side and finally 17 holes per side with a diameter of 10 mm instead of the 55 holes per side in the existing pipe are presented in Fig. 5. The longitudinal pitch between holes in this design was maintained constant along the length at 50 mm. Despite the discontinuities in flow which ensue due to the changes in hole diameter this improved design clearly resulted in a much more uniform flow distribution through the bed with a variation of approximately 1.50:1 along the length of the sparge pipe. Re-circulation in the “earlier” holes was still a problem and a number of modifications including chamfering the holes and fitting nozzles to the early holes were studied with limited success. Moreover the overall flow rate through this design was only 0.5% greater than that through the original pipe.

However it is possible to increase the overall flow rate if a somewhat poorer distribution can be tolerated. Again an iterative process involving a large number of different designs resulted in the so-called sparge pipe B in which the holes were gradually reduced in diameter from 15 mm to 10 mm in 1 mm steps. The longitudinal pitch was maintained at 30 mm for the first 10 holes and then was increased to 35 mm for the next 9 holes whilst finally further increasing the pitch to 40 mm for the remaining holes. The diameter of the “expansion” hole in the end of the pipe was also increased from 10 to 16 mm. These changes in the pitch and diameter of the holes result in sharper discontinuities in the flow

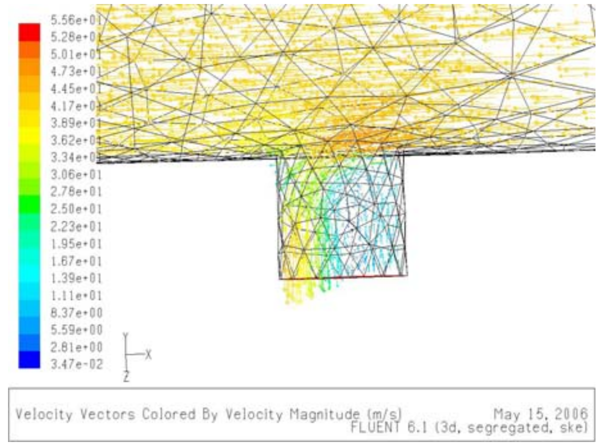

Fig. 3. *Velocity Vectors for the Flow from the First Hole in the Sparge Pipe*

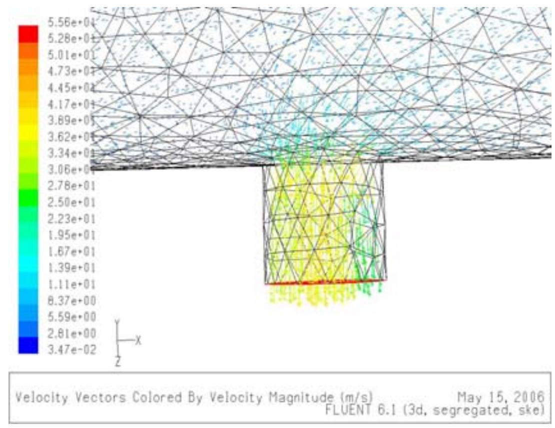

Fig. 4. *Velocity Vectors for the Flow from the Final Hole in the Sparge Pipe*

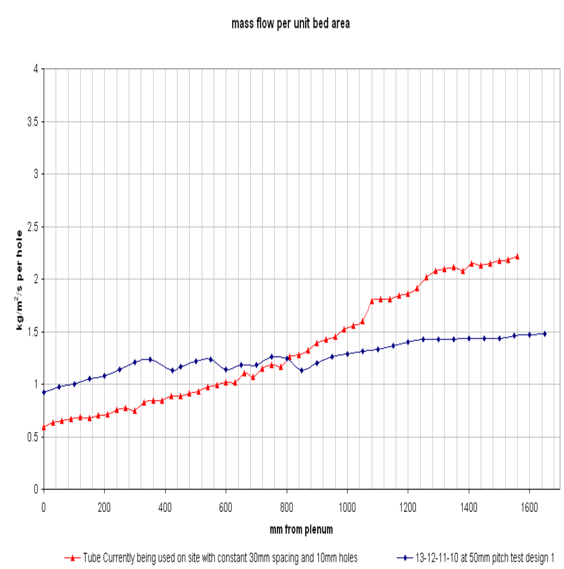

Fig. 5. *Comparison of the Flow Characteristics of Sparge Pipe A with the Original Design*

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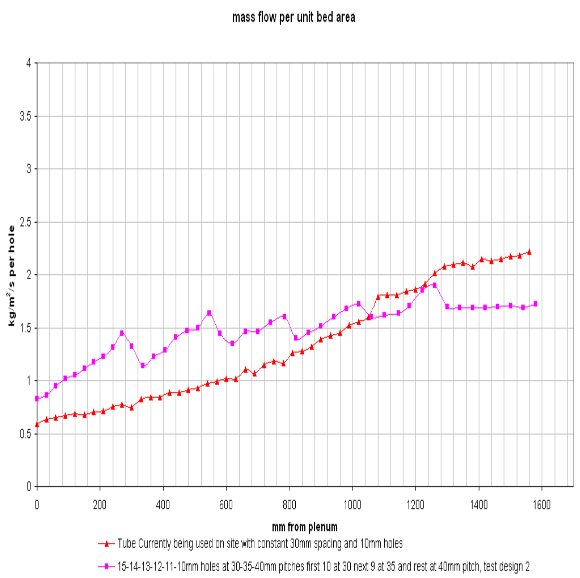

Fig. 6. *Comparison of the Flow Characteristics of Sparge Pipe B with the Original Design*

distribution through the bed, see Fig. 6, but nevertheless the variation in flow along the pipe (slightly over 2:1) is substantially better than that in the existing design. The overall increase in flow rate through this sparge pipe is 9% higher than through the existing design. Sparge pipe B therefore appears to offer a reasonable compromise design since it provides a better distribution together with an increased overall flow rate which in turn will lead to an increased thermal output and improved operation of the fluidised bed hot gas generator.

3. SPARGE PIPE WEAR TESTS

3.1 Experimental Details

Erosion and wear of both the holes and wall of the current sparge pipes can be severe so that a "cold" wear test rig, which operated at near ambient temperatures, was designed and constructed to simulate and investigate the wear characteristics of different sparge pipe designs, see Fig. 7. This initially consisted of three parallel 700 mm long steel sparge pipes mounted in a fluidised bed so that interaction between adjacent pipes can be simulated. The pipe and hole diameters, the hole pitch, and spacing between adjacent pipes were identical to those currently employed on the full size plant. Air was fed separately to each pipe from a large centrifugal fan and the flow rate into and out of each pipe was monitored and controlled by calibrated iris dampers. Consequently the flow conditions at different positions along the full scale sparge pipe can be simulated by varying the flows into, and out of, the pipes.

It is clearly important that this near ambient temperature fluidised bed test rig should behave in a dynamically similar manner to the full scale plant. Therefore a similarity analysis was undertaken, taking into account the relative fluidising gas densities and the Archimedes, Froude and Reynolds numbers in the full scale and model cases, and as a result the test rig was operated with sand with a surface mean particle diameter of 0.3mm and with a fluidising velocity of 1.5 m/s. The depth of the "slumped" model bed above the sparge pipes in an unfluidised condition was maintained at 150 mm to match that in the full scale bed.

Wear patterns over the surfaces of the model sparge pipes were obtained using a multilayer paint technique in which the pipes were sprayed with essentially uniform layers of different coloured paints prior to insertion in the test rig. The wear characteristics of the paints were temperature dependent so that an electrical heater was incorporated after the delivery air fan to ensure that the fluidising air temperature was maintained constant at 55°C throughout the tests. In addition to the visual observation of the wear patterns provided by the coloured paints quantitative data on wear rates were obtained by a profilometric technique. This involved traversing a sensitive stylus over specific regions of the painted pipe before insertion and after removal from the bed using an accurate co-ordinate measurement machine. In this fashion repeatable and precise measurements of the changes in thickness of the paint layers, and hence wear rates, can be obtained. The duration of the tests varied from 36 to 72 hours depending on operating conditions.

This large test rig is cumbersome to operate since a large amount of sand has to be removed and subsequently replaced to allow periodic observation of the wear patterns throughout the tests. Therefore a new more flexible rig was installed to enable a more detailed analysis of wear to be carried out over a range of different hole geometries and flow conditions. This second rig consisted of 6 small individual beds each containing a short single sparge pipe with two sets of holes. The side walls of these beds were positioned to represent the centre to centre spacing between adjacent tubes. The six beds were supplied from a common constant temperature air supply and as previously the flows into and out of the individual tubes can be controlled separately. Multiple beds were used so that a number of tests can be run simultaneously at the same conditions thereby reducing errors which can arise due to differences in the wear characteristics of the paint from test to test. For the same reason two of the beds were always operated at "standard" conditions to provide data for comparison and relative assessment purposes. A general view of this multiple bed rig is presented in Fig 8.

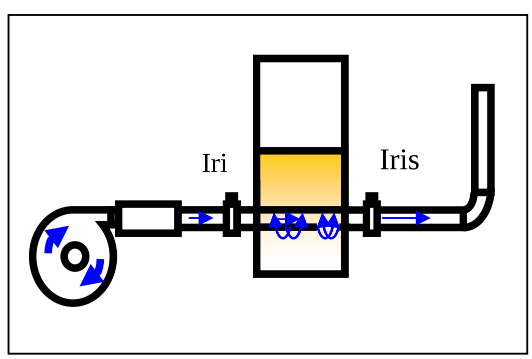

Fig. 7 *Schematic of the Near Ambient Temperature Wear Test Rig*

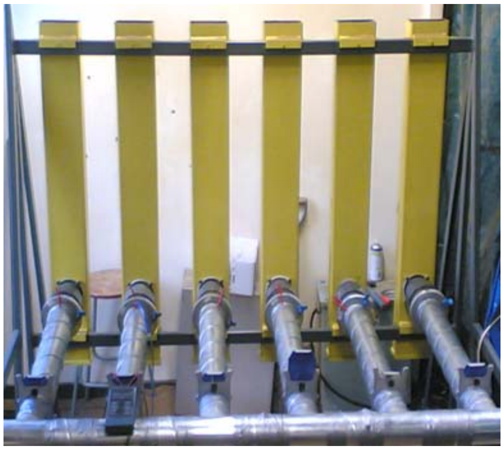

Figure 8. *The Multiple Near Ambient Temperature Fluidised Beds.*

3.2 Preliminary Wear Test Results

Initially the large multiple pipe rig was set up to represent the far end of the sparge pipes and hence the outlets of the three pipes were sealed and the inlet flows adjusted to match those predicted for this end of the full scale plant. The model wear patterns were similar to those observed on the actual pipes with, for example, severe wear clearly occurring just above the holes in both cases, see Figure 9. Moreover the paint patterns indicated that severe wear and erosion can occur at the inside of the holes and this agrees well with the elongation of the holes which frequently ensues in practice. It was also noted during the tests that a comparatively large quantity of bed sand can become entrained into the pipes. This entrainment of sand is also observed in practice on site and as a result the sparge pipes require regular internal cleaning. It therefore appears that the cold tests can reasonably reproduce the main features of wear and entrainment on the actual sparge pipes so that the technique was employed provide quantitative information on the effects of changing the angle of inclination of the holes.

The smaller more flexible test rig with six fluidised beds was employed to investigate the effect of varying the angle of inclination (below the horizontal) of the 10 mm diameter sparge pipe holes. The current holes in the existing design are positioned at an angle of 35° and further tests were conducted with hole inclination angles of 25, 20 and 15°. The results, see Fig 10, clearly indicate, despite the scatter in the data, that reducing the angle of inclination below 20º substantially reduces the maximum rate of wear. Thus, for example, the rate of wear is reduced by about 60% at an angle of 15° when compared with that with the holes inclined at the current position of 35°. The position and shape of the paint wear patterns were also changed by varying the angle of inclination At the shallower angle of 15° the region of paint wear is shifted towards the top of the tube and is more spread out and less severe. In contrast at the current angle of 35° the wear occurs just above the holes and appears to be less widespread but more severe locally. Overall it appears that substantially less severe

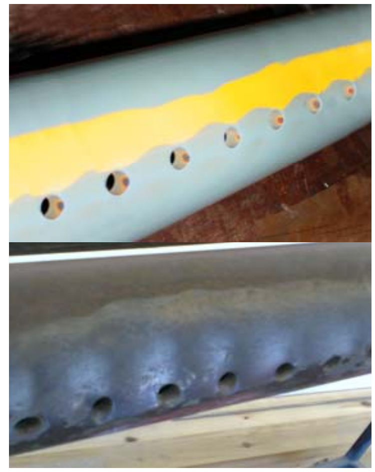

Fig. 9 *Model and Full Scale Sparge Pipe Wear Patterns*

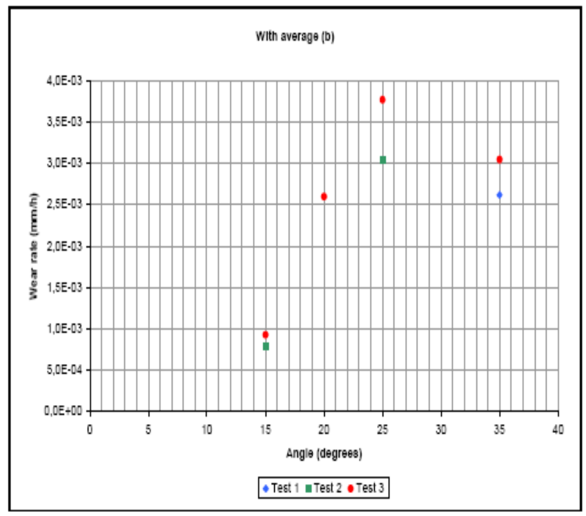

Fig. 10. *The Effect on Paint Layer Wear Rates of Varying the Angle of Inclination of the Holes*

wear would occur if the sparge pipe holes were inclined at a shallower angle of 15°. This inclination is still sufficient to prevent sand infiltrating into the pipe when the bed is not fluidised.

Further work is required to investigate the effects of varying the hole diameter and pitch as well as changing the air velocity exiting the holes. It should also be noted at this stage that the small individual fluidised beds only contain a single pipe so that potential interactions between the jets from adjacent pipes is not simulated. In addition the presence of the side walls in these small beds may also affect the wear rates. Consequently a number of the more promising hole arrangements will need to be assessed in the large three pipe fluidised bed. Nevertheless at this stage it appears that reducing the angle of inclination of the holes may well be beneficial from the point of view of sparge pipe wear and erosion.

4. CONCLUSIONS

The current existing design of sparge pipe contains 55 holes along each side of the pipe. The diameter of these holes is 10 mm and they are spaced uniformly at a pitch of 30 mm along the length of the pipe and inclined downwards at an angle of 35º from the horizontal. The predicted performance of the sparge pipe air distributor can be improved by changing the geometry of these holes. For example whilst maintaining the overall flow rate the variation in air flow through the bed along the length of the pipe can be reduced to approximately 1.50:1 instead of the current distribution of about 3.45:1. Alternatively by tolerating an increase in this variation to approximately 2.0:1 the predicted overall flow rate can be increased by 9% when compared with the existing value. Wear tests using near ambient temperature fluidised beds and a multi-layer paint technique indicate that wear and erosion of the current sparge pipes can be significantly reduced by reducing the angle of inclination of the holes to 15º below the horizontal. Consequently both the flow and wear characteristics can be improved by altering the design of the pipe

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