Experimental Investigation of Guide Vanes in S-Shaped Ducts

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Abstract

The paper presents the results of experimental measurements conducted to investigate the influence of guide vanes on the flow inside a multiply curved S-shaped duct designed to convey the gas turbine flue gases to the inlet of a heat recovery steam generator, in a combined cycle plant. The experimental rig includes a model of the S-shaped duct attached to a model of the steam generator. Measurements are first made for the flow inside the duct in absence of guide vanes; large separation zones are observed. Several sets of differently shaped and located guide vanes are then introduced in the duct and the corresponding flow pattern is measured and reported. It is revealed that with the proper design of the guide vanes flow separation may be avoided and both uniformity and orthogonality of the flow are vastly improved at the first bank of tubes in the steam generator , thus satisfying the design requirements.

Introduction

In a combined cycle plant, the heat energy in the flue gases leaving a gas turbine is utilized by ducting the gases into a heat recovery steam generator, HRSG. The common arrangement involves exiting the gas turbine flue gas into a diverter box, which directs the gas either up a chimneystack or into a duct connected to the HRSG inlet.

These inlet ducts often display complex geometries and expanding cross-sections, imposed by the need to by pass installed equipment and to connect inlet-outlet ports of different shapes and sizes, and located at different heights. Thus it is highly probable that the free internal flow inside these ducts will exhibit large separation zones leading to unacceptably large pressure drops (affecting over-all cycle efficiency), in addition to highly non-uniform and non-orthogonal flow at the duct end. Since, the gas path within the HRSG unit is designed for uniform and orthogonal flow, any deviation from these conditions adversely affects the rate of heat transfer from the gas to water, as demonstrated by [1, 2].

This problem was encountered during the design of an S-shaped inlet duct for a combined power plant in Egypt. The solution was proposed in the form of providing better control and guidance to the internal flow through the use of internal guide vanes. Thus the present research was initiated with the objective of studying the free flow in the S-shaped inlet duct and investigating the effect of introducing various guide vane shapes and locations, with the goal of reducing internal recirculation of the flow and achieving an acceptable degree of flow uniformity and orthogonality at the exit of the inlet duct. The investigations were based on experimental measurements, the results of which are presented in the present paper.

Test Facility

Experimental Apparatus

Fig.1 displays a schematic diagram of the test rig, which employs a forced draft wind tunnel. Air first passes from the fan to a settling chamber to isolate the vibration induced by the motor fan assembly, then through a three dimensional nozzle of area ratio 3:1 to eliminate mean flow non-uniformity and to reduce turbulence level. Finally, air passes through a flow straightener to eliminate remaining non-uniformities before entering the test section.

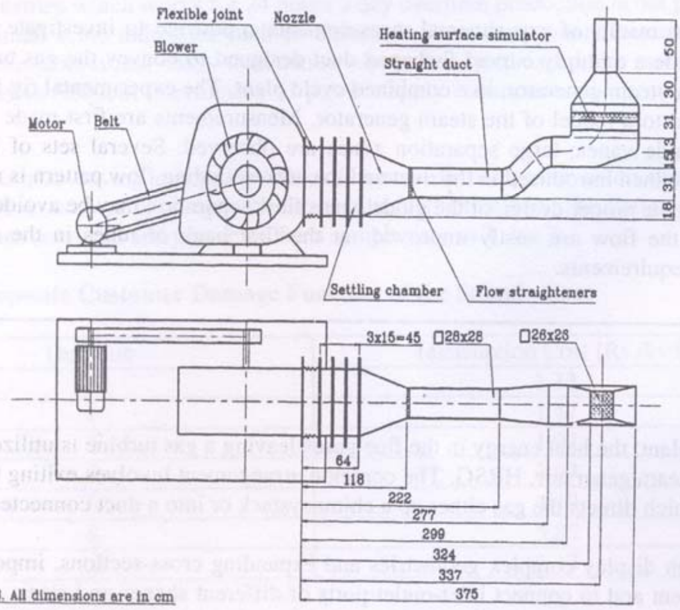


Fig.1 Experimental test rig

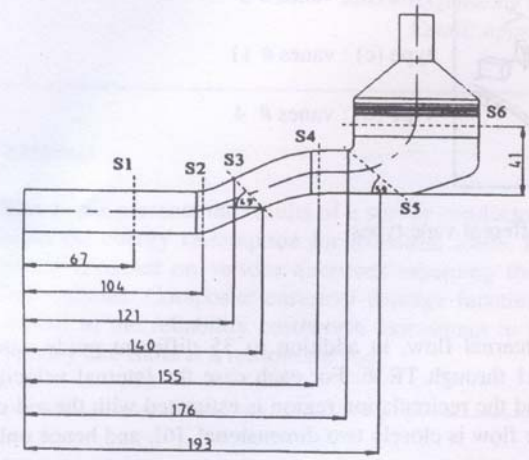
The test section was built of plexi-glass to enable flow visualization, and conforms to a 1:20 model of the actual inlet duct and HRSG; except that, for practical reasons, the tube bundles of the actual HRSG were replaced by uniformly distributed blockages in the form of foam screens. The blockages were positioned in the same relative locations of the tube bundles and their porosity was chosen so as to give the same ratio of pressure drop/kinetic energy of flow.

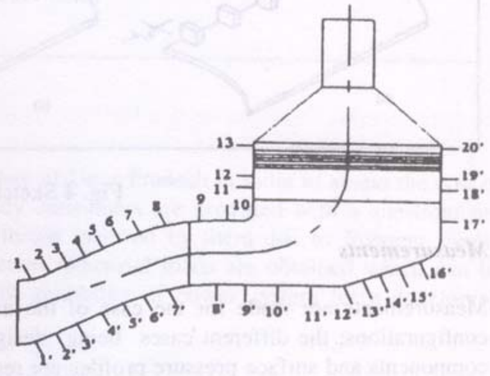
Measured Quantities

The measurable quantities include flow velocity measurements and wall static pressure measurements. In addition, flow visualization is achieved employing thin yellow strings glued to the sidewalls of the duct.

Velocity Measurements: A conventional 3-hole probe connected to a Testo 512 digital differential micro-manometer was employed to measure the local velocity components in two dimensions. The measurements were conducted over 6 test sections whose locations are revealed in Fig. 2, and referred to by S1, S2, .S6. The number of measurement points over each section ranged between 7 x 7 points at section S1 to 19 x 7 points at section S6.

Surface Pressure Measurements: thirty-three surface pressure taps were distributed along the upper and lower surface of the central plane of the duct, as displayed in Fig. 3. A bank of inclined U-tube manometers was employed to measure the static pressures.





N.b. all dimensions in cm and not to scale

Fig.2 Velocity measurement planes

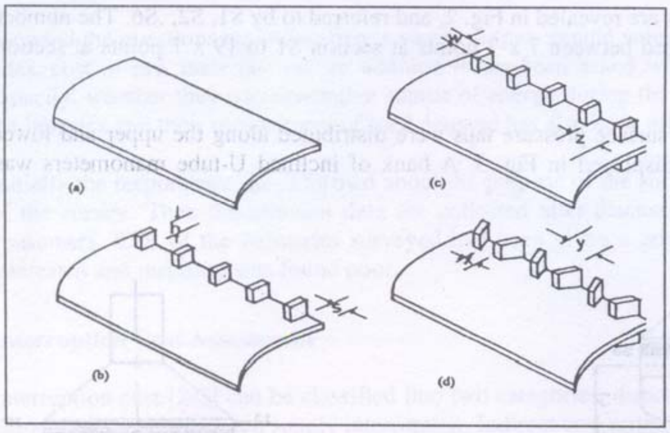
Fig.3 Surface pressure taps

Guide Vanes

The channel considered here, features rapid flow area increases resulting in large adverse pressure gradients coupled with sharp changes in direction, both of which encourage internal flow separation and non-uniformity of the flow at its exit plane, as indicated in [3],[4]. Thus guide vanes need to be installed at critical locations within the duct in order to control the internal separation of the flow and to improve its orthogonality and uniformity at entrance to the HRSG. Both the shape and location of the guide vanes have a strong influence on the guided flow; indeed a poor choice could result in a deterioration of the flow over that of the unguided one. The optimum set should provide the required guidance to the flow with a minimum number of vanes and vane size, thus reducing flow resistance (hence pressure drop) and minimizing equipment cost.

In this work 12 different guide vane shapes and types are tested, designated 1 to 12, respectively. They comprise fin-less vanes, vanes with fins on one side and on both sides, and vanes with vortex generators on both sides as sketched in Fig. 4, based on the works of other researchers [5].

Details of the guide vane geometries, together with other measurement details may be found in [6]. The shape of the individual vanes evolves from the results of flow visualization and preliminary experiments, as well as intuition and previous experience. The vane locations are selected in the same way.



w = z = h = 5 cm , y = 6 cm, x = 3 cm, s= 4cm

type (a) : vanes # 1,2,3,6,7,8,9,10 &12

type (b) : vanes # 5

type (c) : vanes # 11

type (d) : vanes # 4

Fig. 4 Sketch of the different vane types

Measurements

Measurements are made for the case of the unguided internal flow, in addition to 35 different guide vane configurations; the different cases being designated TR1 through TR36. For each case the internal velocity components and surface pressure profiles are recorded, and the recirculation region is estimated with the aid of string flow indicators on the side walls. It is found that the flow is closely two dimensional, [6], and hence only the profiles along the mid plane are reported here.

Fig. 5 displays the velocity vectors in the mid plane of the duct for the flow in absence of guide vanes, the velocity vectors indicating in both magnitude and direction the measured local velocity. Fig.6 presents the corresponding pressure distribution along the upper and lower surface of the duct, displayed in the form of local pressure coefficients C_p defined as:

$$C_p = 2\,(P_s - P_1)\,/\,\rho\,\bar{v}^2 \qquad (1)$$

where P_s is the local static pressure , P_1 is the static pressure at the first measurement location, ρ is the air density and $\bar{v}$ is the average velocity over the section.

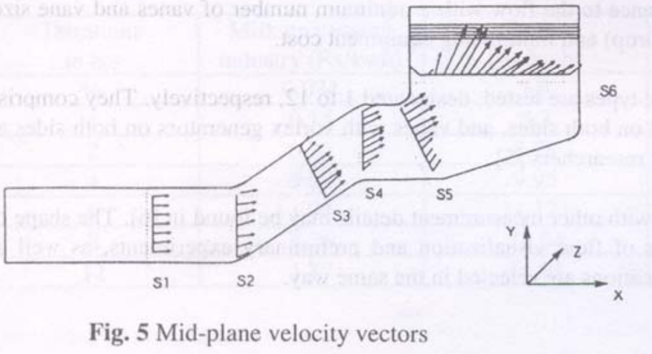


Fig. 5 Mid-plane velocity vectors

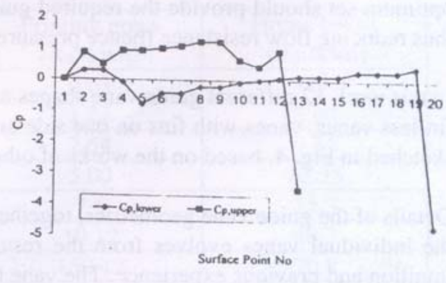


Fig.6 C_p along upper/lower walls

Examination of the velocity profile at S6 reveals high non-uniformity and non-orthogonality; in addition there is a strong indication of a small inner corner recirculation zone. The profiles at S4 and S5 also reveal high non-uniformity and indicate the presence of a large recirculation zone at the bottom corner, which was also confirmed by flow visualization.

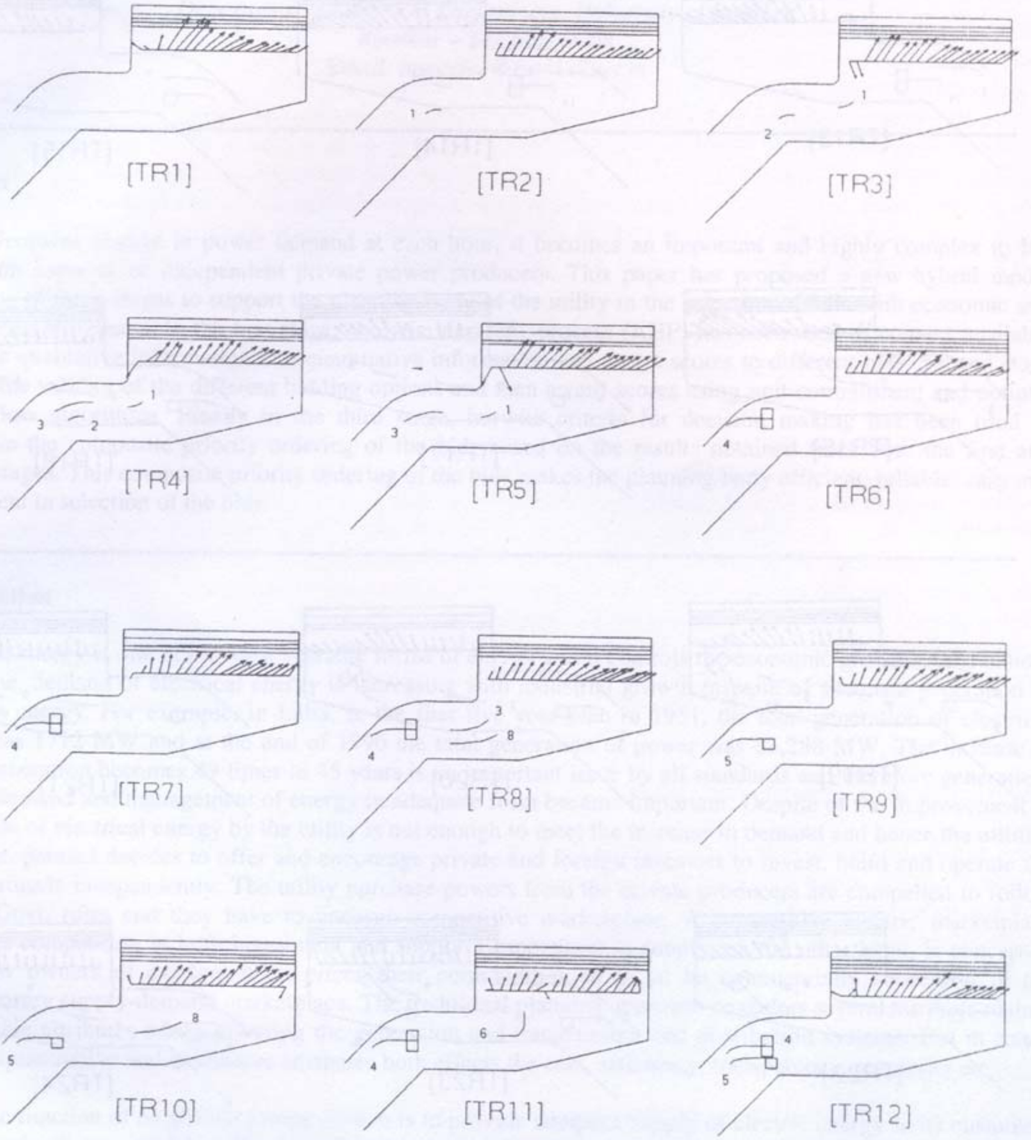


Fig. 7 Measured velocity vectors for trials TR1 to TR12

Fig. 7 displays the measured velocity vectors at S6 for trials TR1 to TR12; the corresponding guide vane configuration is displayed simultaneously. Fig 8 displays the velocity vectors for trials TR13 to TR24, while Fig. 9 displays the velocity vectors for trials TR25 to TR36.

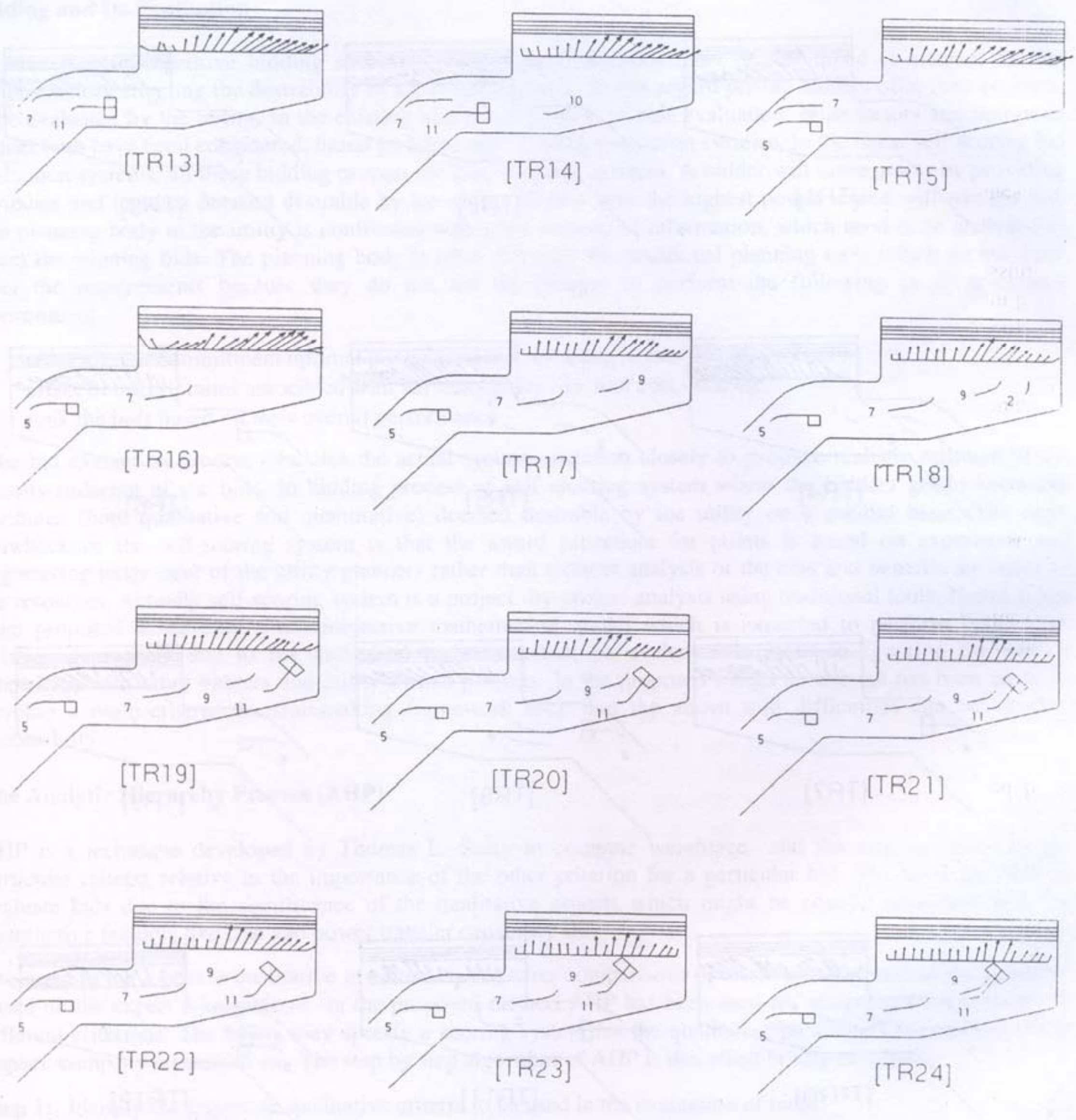


Fig. 8 Measured velocity vectors for trials TR13 to TR24

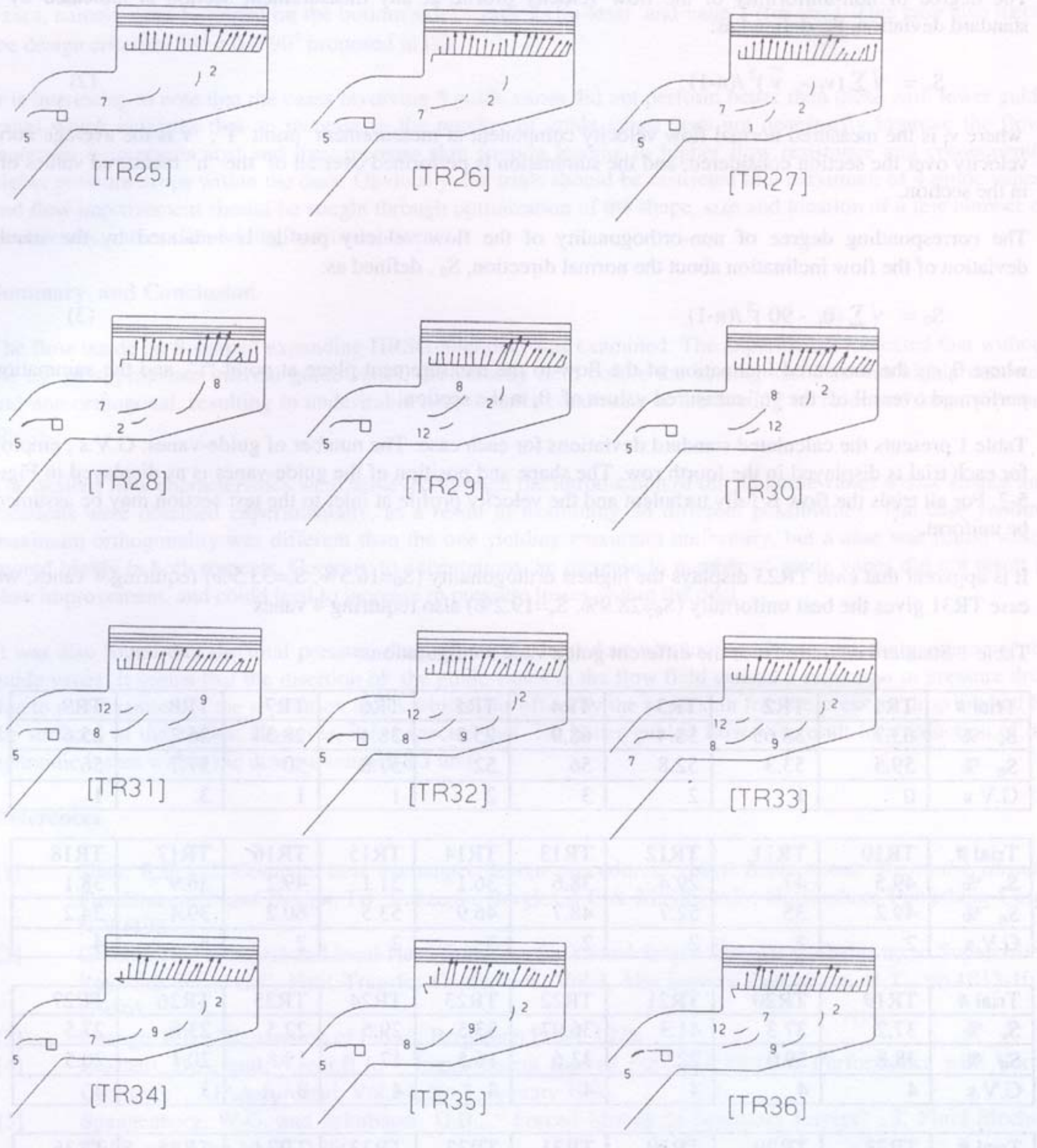


Fig. 9 Measured velocity vectors for trials TR13 to TR24

Visually it is obvious that some guide vane configurations produce better guidance to the flow than others; however, more accurate quantifiable estimates are made as follows:

The degree of non-uniformity of the flow velocity profile at any measurement section is indicated by the standard deviation, S_v, defined as:

$$S_v = \sqrt{\Sigma (v_i - \bar{v})^2 /(n-1)} \qquad (2)$$

where v_i is the measured normal flow velocity component at measurement point "i", $\bar{v}$ is the average normal velocity over the section considered, and the summation is performed over all of the "n" measured values of v_i in the section.

The corresponding degree of non-orthogonality of the flow velocity profile is indicated by the standard deviation of the flow inclination about the normal direction, S_θ, defined as:

$$S_\theta = \sqrt{\Sigma (\theta_i - 90)^2 /(n-1)} \qquad (3)$$

where θ_i is the measured inclination of the flow to the measurement plane at point "i", and the summation is performed over all of the "n" measured values of θ_i in the section.

Table 1 presents the calculated standard deviations for each case. The number of guide-vanes, G.V.s , employed for each trial is displayed in the fourth row. The shape and position of the guide-vanes is as displayed in Figures 5-7. For all trials the flow is fully turbulent and the velocity profile at inlet to the test section may be assumed to be uniform.

It is apparent that case TR23 displays the highest orthogonality (S_θ=16.5%, S_v=33.5%) requiring 4 vanes, while case TR31 gives the best uniformity (S_θ=28.9%, S_v=19.2%) also requiring 4 vanes

Table 1 Standard deviations for the different guide vane configurations

Trial #	TR1	TR2	TR3	TR4	TR5	TR6	TR7	TR8	TR9
S_v %	63.7	38.65	58.4	68.9	25.3	38.4	28.34	26.2	25.6
S_θ %	59.5	53.3	52.8	56	52	57.8	50	57.7	56
G.V.s	0	1	2	3	2	1	1	3	1

Trial #	TR10	TR11	TR12	TR13	TR14	TR15	TR16	TR17	TR18
S_v %	49.5	47	29.4	38.6	36.1	31.1	49.2	36.9	38.1
S_θ %	49.2	35	52.7	48.7	46.9	53.5	60.2	39.4	34.2
G.V.s	2	2	2	2	3	2	2	3	4

Trial #	TR19	TR20	TR21	TR22	TR23	TR24	TR25	TR26	TR27
S_v %	37.2	37.3	41.3	36.97	33.5	29.5	22.5	23.8	27.5
S_θ %	38.8	39.6	22.9	33.6	16.5	17	18.8	20.1	20.5
G.V.s	4	4	4	4	4	4	3	3	4

Trial #	TR28	TR29	TR30	TR31	TR32	TR33	TR34	TR35	TR36
S_v %	39.5	35.4	26.2	19.2	22	26.1	27.5	26.5	29.2
S_θ %	19.7	25.2	28.2	28.9	22.5	25.7	23.1	24.8	22.3
G.V.s	4	4	4	4	5	5	4	4	5

The best compromise seems to be case TR25 which gives (S_θ=18.8%, S_v=22.5%) , and requires only 3 guide vanes, namely vane 5 (finned on the bottom side) , vane 7 (fin-less) and vane 2 (fin-less). This case also meets the design criterion $60^\circ < \theta < 90^\circ$ proposed in [2].

It is interesting to note that the cases involving 5 guide vanes did not perform better than those with fewer guide vanes which indicates that an increase in the number of guide vanes does not necessarily improve the flow; moreover it increases cost and may increase skin friction leading to higher flow resistance and consequently higher pressure drops within the duct. Obviously, the trials should be restricted to a maximum of 4 guide vanes, and flow improvement should be sought through optimization of the shape, size and location of a few number of guide vanes, rather than adding additional ones.

Summary and Conclusion

The flow inside an S-shaped expanding HRSG inlet duct was examined. The experiments indicated that without the use of appropriate internal guide vanes, the velocity field before the heating surfaces was highly distorted and non-orthogonal, resulting in undesirable heat transfer conditions at the heating surfaces and large pressure losses.

The desired flow characteristics were achieved through the introduction of only 3 guide vanes whose shapes and locations were obtained experimentally, as a result of examining 36 different possibilities. The case yielding maximum orthogonality was different than the one yielding maximum uniformity, but a case was found which scored highly in both respects. Contrary to expectations, an increase in number of guide vanes did not result in flow improvement, and could lead to increase in pressure losses within the duct.

It was also found that the total pressure drop across the inlet duct was hardly affected by the presence of the guide vanes. It seems that the insertion of the guide vanes in the flow field caused a reduction in pressure drop due to minimization of the separation zones which was offset by the extra skin friction pressure drop created by the surfaces of the blades. However, it is expected that the better guided flow will result in a reduction of the hydraulic losses within the downstream HRSG unit.

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