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ABSTRACT

Conversion efficiency, durability and pressure drop of automotive exhaust catalysts are dependent on the flow distribution within the substrate. This study examines the effect on flow distribution using substrates which feature contoured front faces. Three ceramic contoured substrates of equal volume were assessed. Two of the substrates were cone shaped with different cone angles and one had a dome shaped front face. Pressure drop and flow distribution was measured for a range of flow rates and substrate positions. Computational Fluid Dynamics (CFD) simulations were also performed to provide insight into flow behaviour. It is shown how a contoured substrate can provide improvements in flow uniformity and pressure drop when compared to the case of a standard non-contoured substrate.

INTRODUCTION

The wide-angle diffusers often used in standard automotive exhaust catalyst systems create flow separation in the diffuser throat, which produces a maldistributed flow impinging on the front face of the substrate. This can adversely affect conversion efficiency, catalyst durability and pressure loss [1, 2]. One possible method of improving the flow distribution is by shaping the substrate. As an example of this Corning Environmental Products Inc. has developed the Contura™ ceramic substrate [3], as seen in figure 1. The shaped front face also means that the diffuser cone volume can be utilised, increasing the catalyst volume within an unchanged package.

Previous studies have reported on the performance of shaped substrates.

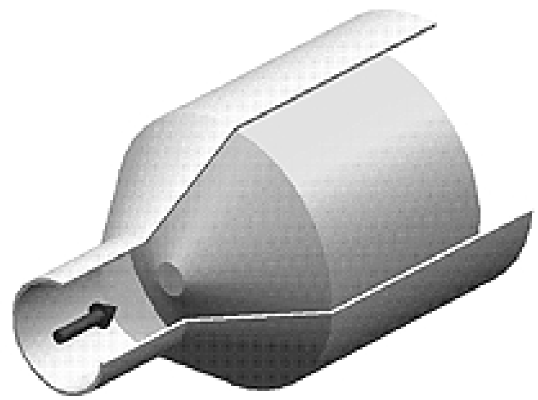

Figure 1. Contura substrate with diffuser

Schönfelder [4] reported results from an experimental and computational investigation of shaped metal substrates. The metal substrates were 90 degree conical in both ends, which meant that the channel length was constant across the diameter. A 16% decrease in the maximum velocity was observed giving a more uniform flow distribution.

Holmgren *et. al.* at Chalmers University of Technology performed an experimental and computational study on shaped ceramic substrates [5]. This study investigated three shaped substrates and compared the results with a standard substrate. Unfortunately the substrate volume was not kept constant which makes comparison difficult. Substrates with 45 degree and 60 degree conical fronts were compared to a dome shaped and a standard substrate. More uniform velocity profiles were achieved compared to the standard substrate.

An experimental and computational study was reported by Corning Inc. [3]. They investigated the flow distribution between a Contura and a standard substrate. CFD was used to optimise the cone angles for flow distribution. Experiments showed a 34% reduction in maximum velocity. The flow uniformity was improved by using Contura substrates compared to the standard substrate. The pressure drop for the Contura substrate was marginally higher compared to the standard substrate.

The objective of this study is to investigate the effect of the substrate shape using equal volume substrates and to try to improve the flow distribution and pressure drop. To achieve this four different substrates have been studied at different flow rates and positions. A standard substrate, for reference is compared to two cone shaped substrates according to the Corning Contura concept and to one dome shaped substrate according to the Coventry University AeroCat concept.

EXPERIMENTAL METHOD

SUBSTRATE DESCRIPTION – All substrates were unwashcoated and taken from the same batch to minimise manufacturing variance. The volumes of the substrates were as close as the manufacturing process allowed (~1.11 dm^3). The substrates were of circular section of diameter 118 mm and cell density of 390 cells per square inch (cpsi). A microscope was used to measure the cell width and wall thickness, which were found to be approximately 1.08 and 0.161 mm respectively. The dimensions of the substrates as received are given in table 1.

Table 1. Summary of external dimensions

measures in mm	Contura 1	Contura 2	AeroCat	Standard
Total length	122.8	126.6	114.4	102.2
Length shaped part	33.6	40.0	27.0	N/A
Length cylindrical part	89.2	86.6	87.4	N/A
Tip diameter	14.7	14.7	N/A	N/A
Front angle (degrees)	33.0	37.8	N/A	N/A

TEST RIG – A schematic layout of the iso-thermal test rig used in this study can be seen in figure 2. The test rig is supplied with compressed air from two receivers via a main valve (1). A pressure gauge (2) monitors the supply pressure, which is reduced from ~100 psi to ~40 psi by a valve (3). A second pressure gauge monitors the rig pressure (4). A safety relief valve rated at 80 psi is used to avoid damage to the rig (5). A filter (6) is used to avoid oil contamination. The mass flow rate is controlled by an adjustment valve (7) and measured using a viscous flow meter (8). The viscous flow meter is connected to a digital manometer FCO16 from Furness Controls. A plenum incorporating a flow straightner (9) is used to avoid swirl components in the flow and a contracting nozzle (10) produces a uniform velocity profile at the diffuser inlet. A 70-degree total angle axisymmetrical diffuser (11) was used in the experiments. The inlet pipe diameter is 48 mm. On the test substrate (12) an outlet sleeve (13) is used to avoid entrainment of surrounding air.

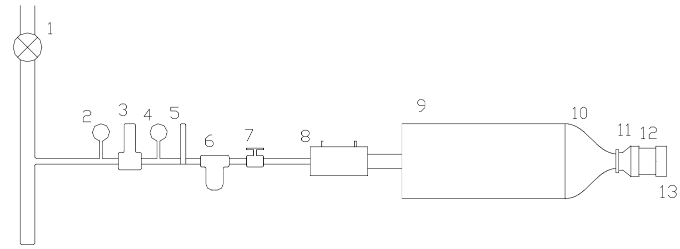

Figure 2. Schematic of iso-thermal flow rig

FLOW DISTRIBUTION MEASUREMENTS – The flow distribution was determined by measuring velocity profiles at the rear of the substrate. For the velocity measurements a TSI IFA 300 Constant Temperature Hot Wire Anemometry (HWA) system was used, as seen in figure 3. The system comprises of a main unit with the HWA bridges, a 2D traverse and the ThermalPro software to control and acquire data. The probes were 5 µm Tungsten/Platinum wire probes, calibrated using a DANTEC calibration rig. The velocity profiles were measured in the outlet sleeve 30 mm down stream of the substrate. Previous work [6] showed that this distance was necessary in order to avoid jets from individual channels. The velocity was also initially measured with a 0.5 mm total head pitot tube. Good correlation was seen which confirmed the calibration of the HWA probe.

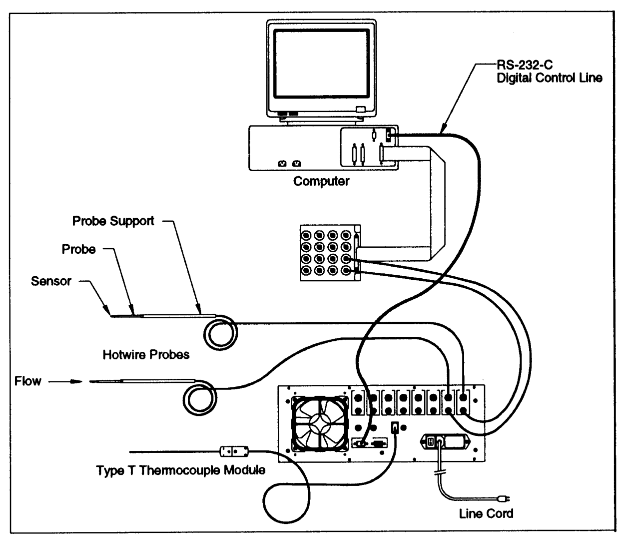

Figure 3. Overview of the IFA 300 System (Courtesy of TSI) [7]

The flow distribution was initially measured along two perpendicular axes for all four substrates at a Reynolds number of 70000. The conclusion from this was that the flow was axisymmetric for all substrates and that measurements only needed to be taken over one axis.

In this study because the substrate length varies radially space velocity is considered as the preferred measure of flow performance. Hence a non-uniformity index was devised to compare the performance of the substrates and was calculated using the mass flow weighted difference between the local and mean space velocity integrated over the substrate face. The local space velocity and the mean space velocity are defined as in equation 1 and 2 respectively.

$$V_{spi} = \frac{V_i}{L_i} \tag{1}$$

$$\bar{V}_{sp} = \frac{1}{\dot{m}} \int_A V_{spi} \delta \dot{m} \tag{2}$$

The variation of the space velocity, σ_{Vsp}, is defined according to equation 3.

$$\sigma_{Vsp} = \frac{1}{\dot{m}} \int_A \left| V_{spi} - \bar{V}_{sp} \right| \delta \dot{m} \tag{3}$$

This results in the non-uniformity index over the cross section of the substrate according to equation 4.

$$\psi = \frac{\sigma_{Vsp}}{\bar{V}_{sp}} \times 100 \tag{4}$$

A non-uniformity index of zero means that the space velocity is uniform across the substrate.

PRESSURE DROP MEASUREMENTS – The pressure drop was measured for different mass flow rates and substrate positions. Three static pressure tappings were located 40 mm up-stream of the diffuser throat. The tappings were evenly spaced around the diffuser throat and interconnected. A Furness Controls manometer FCO510 was used to take the static pressure readings. The position of the substrate is defined relative to the baseline position as seen in figure 4. From the baseline the substrates were moved downstream 3, 5, 10, 15, 20, 25 and 30 mm.

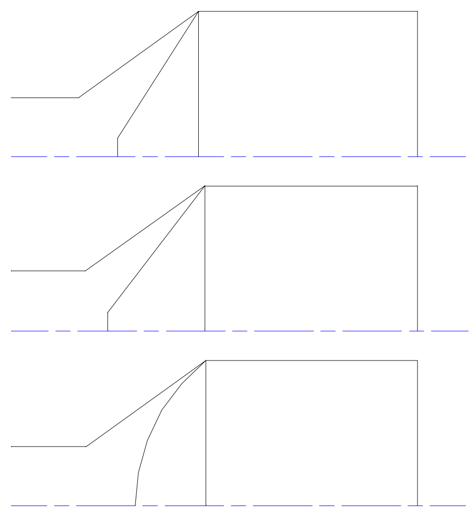

Figure 4. Schematics of substrates in baseline position

EXPERIMENTAL RESULTS

The static pressure drop non-dimensionalised by the inlet dynamic pressure is given in table 2 along with the non-uniformity index, Ψ. The space velocity profiles for all four substrates at different Reynolds numbers can be seen in figures 5-8. A comparison of all substrates at Re = ~85000 can be seen in figure 9.

Table 2. Experimental results

Substrate	Actual Re	*ΔPs	Ψ
Standard	3650	1.01	33.1
“	5300	0.68	40.7
“	7060	0.53	46.6
“	9010	0.41	48.5
Contura 1	3470	1.13	19.4
“	4990	0.77	22.2
“	6680	0.61	25.3
“	8230	0.49	26.1
Contura 2	3470	1.15	22.5
“	4850	0.84	23.3
“	6670	0.66	25.1
“	8260	0.53	25.0
AeroCat (AC)	3450	1.14	18.8
“	4960	0.78	22.3
“	6740	0.58	25.5
“	8630	0.42	27.9
Inverted AC	8740	0.43	45.2
AC 3mm down	8470	0.39	25.2

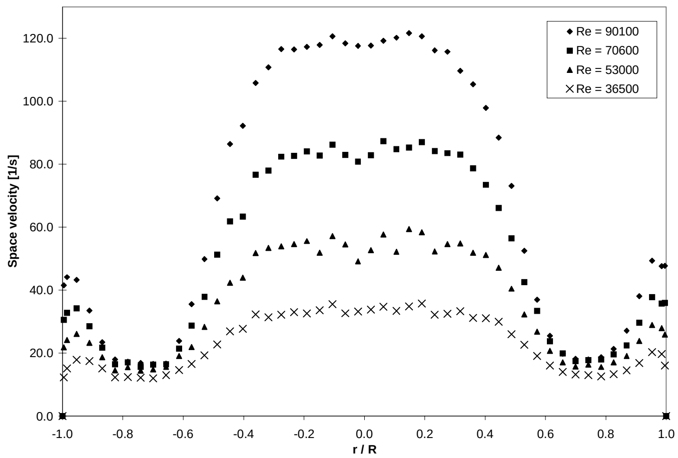

Figure 5. Flow distribution for the Standard substrate

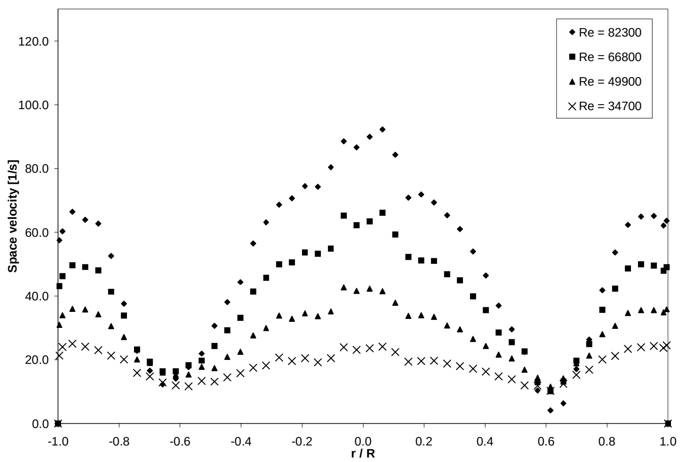

Figure 6. Flow distribution for Contura 1

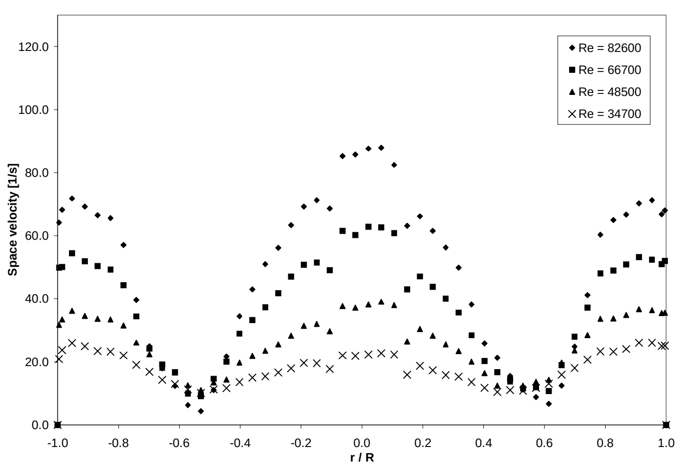

Figure 7. Flow distribution for Contura 2

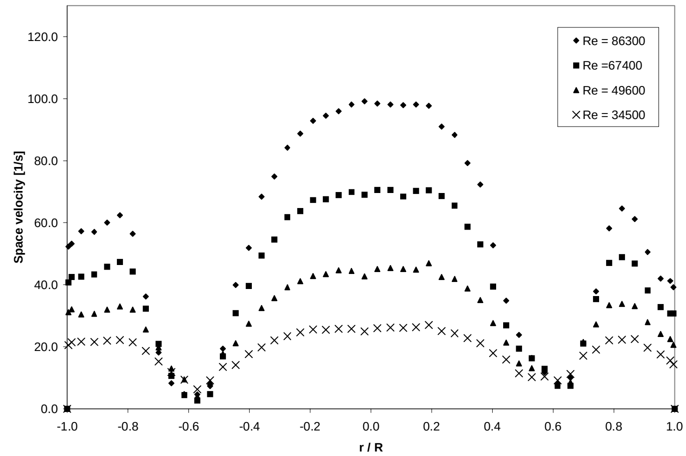

Figure 8. Flow distribution for AeroCat

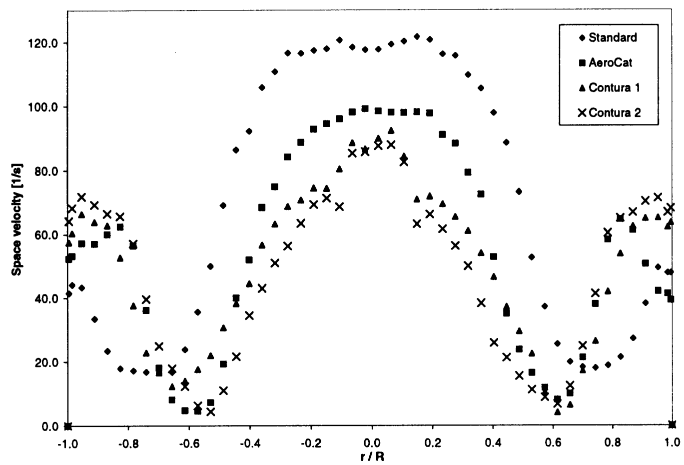

Figure 9. Flow distribution at Re = ~85000

As can be seen in figure 9, the flow distributions for the three shaped substrates are different to the standard substrate but relatively similar to each other. All contoured substrates featured higher space velocity near the outer radius compared to the standard substrate with a reduction in the centre of the substrate.

Clearly the affect of the shaped substrates is to redirect the flow from the centre to the outer circumference, resulting in a more uniform space velocity distribution as evidenced by the improvement in the non-uniformity index, Ψ as shown in table 2. It should however be noted that this also produces a lower minimum space velocity than the standard substrate at a non-dimensionalised radius of ± 0.6.

At the centre of both the Contura substrates a pronounced plateau of elevated space velocity is observed where the flow impinges directly on the flat front face of the substrate. For the Contura substrates there also appears a local minimum space velocity either side of this plateau, figure 7. This is believed to be a consequence of flow separation occurring at the outer radius of the flat front face. The effect seems more pronounced for Contura 2 presumably because of its sharper cone angle.

The static pressure drops for the four substrates at different positions and flow rates can be seen in figures 10-13.

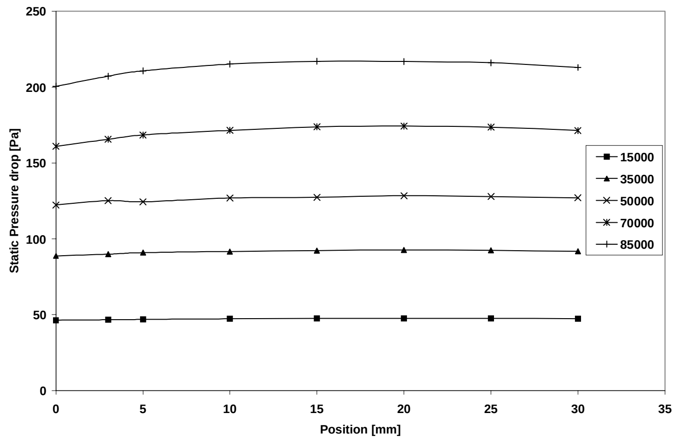

Figure 10. Standard substrate pressure drop at different positions and Re

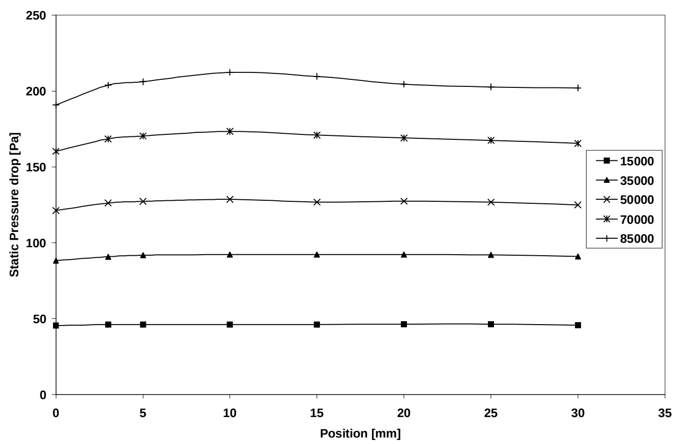

Figure 11. Contura 1 pressure drop at different positions and Re

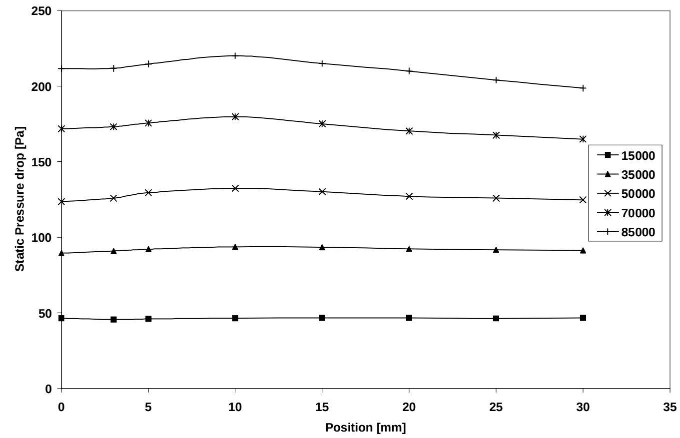

Figure 12. Contura 2 pressure drop at different positions and Re

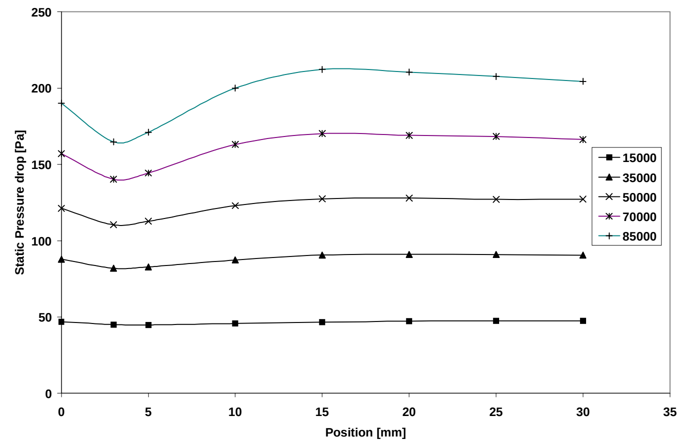

Figure 13. AeroCat pressure drop at different positions and Re

As seen the Contura 1 and the AeroCat produced very similar pressure drops in the baseline position. When the position is changed the pressure drop for the Contura 1 increases. The situation is the opposite for the AeroCat where a local minimum is found ~ 3.5 mm downstream of the baseline. A velocity profile was taken at the 3 mm position for comparison with the baseline position as seen in figure 14. The flow distribution improves slightly with higher space velocities occurring near the wall. The deep troughs observed at non-dimensional radii of ± 0.6 are however unchanged.

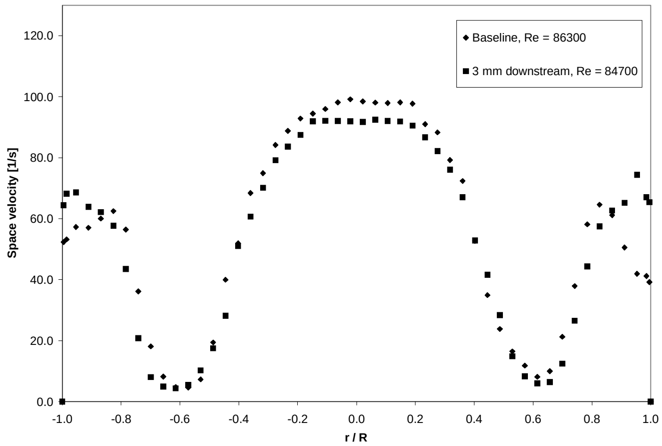

Figure 14. AeroCat in baseline position compared to the 3 mm downstream position

To investigate if it is the shape of the front face or the increased resistance due to increased channel length that dominates the change in flow distribution the AeroCat substrate was inverted so that the shaped face now faced downstream. The velocity profile was again measured 30 mm downstream of the centre of the substrate. It was found that the flow redistribution effect was largely shape dependent as shown in figure 15. The space velocity profiles for the standard and inverted AeroCat substrates are of the same form whereas the AeroCat baseline clearly shows the flow redistribution towards the periphery. A comparison of the standard and inverted AeroCat substrates shows, however, that the latter gives a smoother profile largely as a result of the longer central channels.

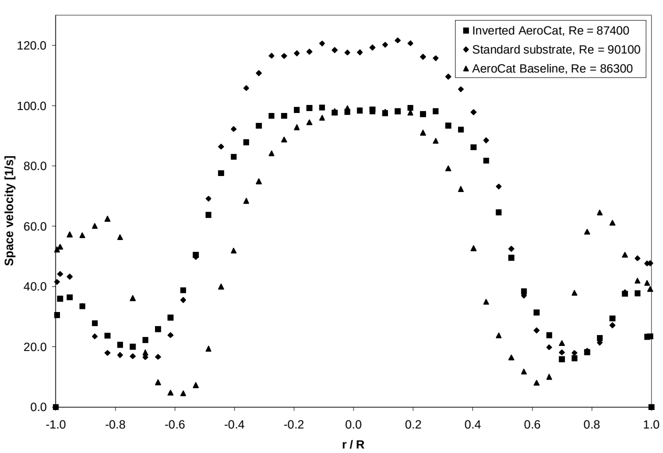

Figure 15. Comparison between the inverted AeroCat, AeroCat baseline and the Standard substrate

CFD PREDICTIONS

To aid the understanding of the flow behaviour in the diffuser, CFD predictions were performed using the commercially available software package Star-CD. Predictions were performed for Contura 1 and the Standard substrate for Re = ~ 70000. To simulate the substrate, a porous medium approach was used with the pressure drop prescribed using the Hagen-Poiseuille equation appropriate for square channels [6]. The non-linear k-ε turbulence model was used in the high Reynolds number regions and the Norris Reynolds model in the near wall region. All variables were discretised using a second order differencing scheme. The flow is assumed to be iso-thermal, incompressible and axially symmetric. Hence only a 5-degree wedge was simulated with symmetry planes defined at the wedge faces. The experimental results can be seen in figure 16 and the predictions in figure 17.

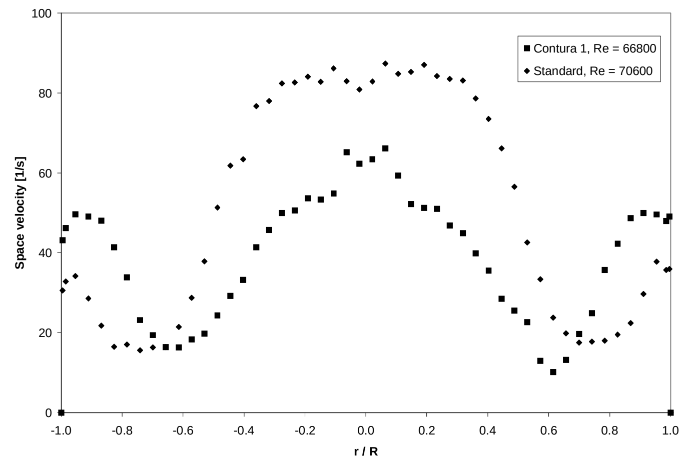

Figure 16. Experimental space velocity profiles for the Contura 1 and Standard substrate

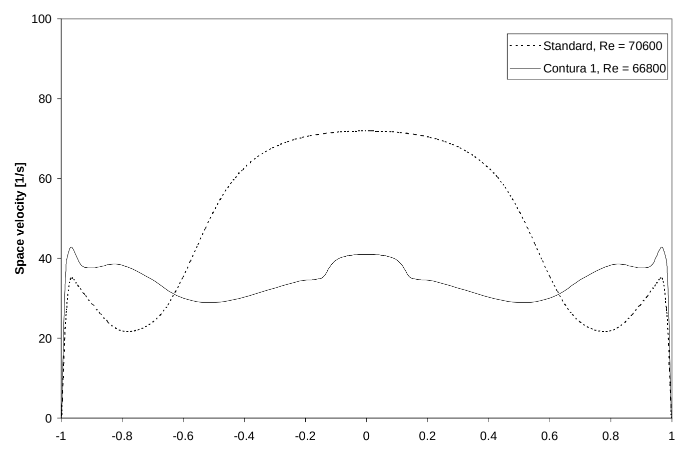

Figure 17. Predicted space velocity profiles for the Contura 1 and Standard substrate

The experimental and computational results are in qualitative agreement whereas the quantitative agreement is poor with predictions giving a much flatter flow distribution. This phenomenon has been reported in previous work [6]. The predicted non-uniformity index for the Contura 1 and Standard substrates is 9,96 and 37.5 respectively.

The main problem is believed to be associated with properly accounting for flow entrance effects into the substrate when the flow impinges obliquely on the front face. Work has been undertaken to model these entrance effects for standard substrates but further work will be needed for substrates featuring contoured faces [8].

However the simulations do provide some insight into the flow structure. Figures 18 and 19 show particle tracks for both simulations. They clearly show that the separated region in the diffuser has been significantly reduced with the flow directed towards the walls at the front face of the substrate.

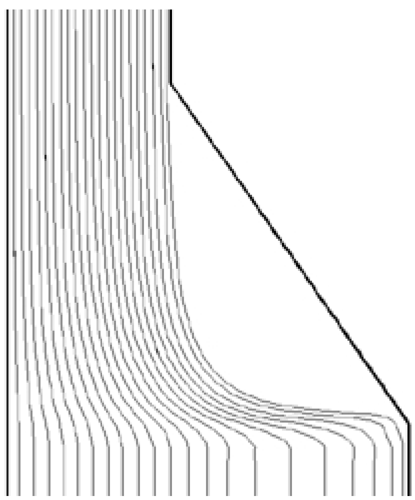

Figure 18. Particle tracks for the Standard substrate geometry

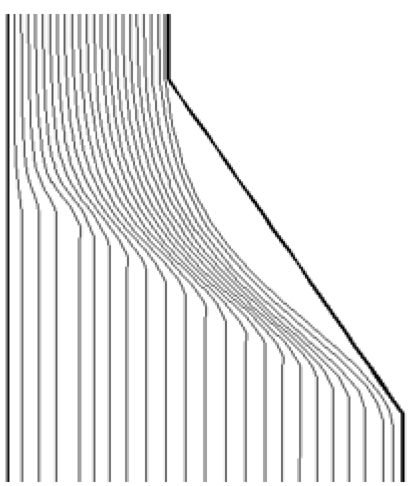

Figure 19. Particle tracks for the Contura 1 geometry

Finally it should be remarked that uniformity in space velocity, whilst providing a useful indication of steady state conversion for mass transfer limited reactors is only one measure of performance. Equally important is the distribution of temperature across the substrate. For systems with significant heat loss near the walls then forcing the flow towards these outer regions may impair conversion efficiency. Also the effect of shaped substrates on catalyst light-off would need to be considered.

CONCLUSION

An experimental and computational investigation of the flow performance of ceramic contoured substrates has been undertaken. It has been shown that the flow distribution and pressure drop can be improved by using shaped substrates.

By using shaped substrates the diffuser volume can be partially utilised. The Contura 1 and 2 utilise 47.9% and 57.7% respectively in their baseline positions whereas the AeroCat utilise 59.1% in its baseline position and 48.1% when located 3 mm downstream. This enables an increase of catalyst volume within an unchanged package.

The contoured substrates force the flow towards the walls with the consequence that the maximum space velocity in the centre of the substrate is lowered. However there are secondary peaks generated towards the walls. Lower maximum space velocity should result in a higher resistance to both thermal degradation and chemical poisoning.

A non-uniformity index, Ψ, was derived to quantify the variation in space velocity across the substrate. The shaped substrates gave significant reductions in Ψ, up to 48 %, compared to the standard substrate. Pressure loss and flow distribution were found to be dependent on axial location for the AeroCat substrate. Minimum pressure loss was found when positioned 3 mm downstream of the baseline position. In this configuration the maximum space velocity is 25% lower and the static pressure drop is 18% lower compared to the standard substrate.

Low velocity regions are found for all the shaped substrates at non-dimensionalised radii of ± 0.6. This is an unwanted feature, which requires more work to eliminate.

Unwanted effects due to substrate geometry were observed for the Contura velocity profiles where local flow separation was observed at the edge of the flat front face.

The effect caused by shaped substrates is totally dominated by the shape of the front face and not the increased channel length and hence resistance. To further improve the shaped substrate concept both ends of the substrate could be shaped without any negative effects on the flow distribution. The space velocity distribution would be more uniform creating a more uniform conversion efficiency across the substrate. Due to the increase in catalyst volume the pressure drop may however increase.

ACKNOWLEDGMENTS

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NOMENCLATURE

A:	Cross sectional area [m^2]
d:	Diameter of inlet pipe [m]
L_l:	Local channel length [m]
m:	Mass flow rate [kg/s]
Re:	Reynolds number in inlet pipe
U_{in}:	Mean velocity in the inlet pipe [m/s]
V_l:	Local velocity [m/s]
V_{spi}:	Local space velocity [1/s]
V_{sp}:	Mean space velocity [1/s]
μ:	Dynamic viscosity [kg/m s]
ρ:	Air density from ideal gas law [kg/m^3]
Ψ:	Non-uniformity index
σ_{Vsp}:	Variance of non-uniformity [1/s]

Reynolds nr.: $\mathrm{Re} = \dfrac{\rho \times U_{in} \times d}{\mu}$

$*\Delta P_S$: Non-dimensional static pressure dro over the system $*\Delta P_s = \dfrac{\Delta P_s}{\frac{1}{2}\rho U_{in}^2}$