

# CFD Parametric Study of Mixers Performance

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**Abstract**—The mixing of two or more liquids is very common in many industrial applications from automotive to food processing. CFD simulations of these processes require comparison with test results. In many cases it is practically impossible. Therefore, comparison provides with scalable tests. So, parameterization of the problem is sufficient to capture the performance of the mixer.

However, the influence of geometrical and thermo-physical parameters on the mixing is not well understood.

In this work influence of geometrical and thermal parameters was studied. It was shown that for full developed turbulent flows ( $Re > 10^4$ ),  $Pe_i \approx \text{const}$  and concentration of secondary fluid  $\sim F(r/l)$ .

In other words, the mixing is practically independent of total flow rate and scale for a given geometry and ratio of flow rates of mixing flows. This statement was proved in present work for different geometries and mixtures such as EGR and water-urea mixture.

Present study has been shown that the best way to improve the mixing is to establish geometry with the lowest  $Pe_i$  number possible by intensifying the turbulence in the domain. This is achievable by using step geometry, impinging flow EGR on a wall, or EGR jets, with a strong change in the flow direction, or using swirler like flow in the domain or combination all of these factors. All of these results are applicable to any mixtures of no compressible fluids.

**Keywords**—CFD, mixing, fluids, parameterization, scalability.

## NOMENCLATURE

$c_{\text{Act}}$	Concentration of secondary fluid
$c_{\text{id}}$	Ratio of secondary fluid flow rate to total flow rate
$D$	Pipe Diameter
$D_{\text{ric}}$	Ricardo Device Diameter
$h$	Clearance between Ricardo device and pipe wall
$H$	Distance from Ricardo device centerline and beginning of elbow
$k$	Turbulent kinetic energy
$L1$	Distance between sections A-A and B-B
$L2$	Distance from Ricardo device centerline and section B-B
$L3$	Length of elbow along centerline
$L4$	Distance from end of elbow and pipe
$L5$	Distance between section C-C and D-D
$L6$	Distance from section D-D to pipe outlet
$M_{\text{tot}}$	Total Flow Rate
$P_{\text{air}}$	Pressure at Air Inlet
$P_{\text{EG}}$	Pressure at EGR Inlet
$R1$	Inner Radius of Elbow
$R2$	Outer Radius of Elbow
$T_{\text{air}}$	Air Temperature
$T_{\text{EG}}$	EGR Temperature
$\alpha$	Angle of Ricardo Device
$\varepsilon$	Turbulent dissipation rate

## I. DESCRIPTION OF ANALYSIS

**T**HEREFORE, many efforts are made to understand the mechanisms and principals of mixing processes. One of the main efforts is CFD modeling [1]–[5].

The mixing process in the EGR mixer and in pipe mixing of two liquids was simulated using CFD. Several different geometries are analyzed for EGR mixer and one for pipe mixing.

ICEM CFD is used for meshing of the model. Two types of mesh are prepared. First one is a tetra only mesh. The second one is a hybrid mesh combining a tetra mesh for one part of the domain and hexa mesh for another one. For the tetra only mesh, it takes more cells to obtain the same resolution as the hybrid mesh and is more expensive for calculations.

On the other hand, a hybrid mesh requires a coupling procedure, which, in these cases, causes some difficulties in convergence.

Steady state CFD calculations are performed with the assumption of incompressible flow and adiabatic wall, inlets, outlet boundary conditions. The density, specific heat, molecular viscosity, thermo conductivity, and diffusivity are assuming the same for EGR and air.

The realizable  $k - \varepsilon$  model was used for modeling of turbulence, because the realizable model is more sensitive to the effects of rapid streamline curvature than the standard  $k - \varepsilon$  model.

Figs. 1–5 show geometries for CFD analysis, parameters definition, boundary conditions, and the cases for CFD simulation are presented give in Tables I-IV.

TABLE I  
SIMULATION CASES – EGR MIXER

Case	Dri c (m m)	h (m m)	H (m m)	L1 (m m)	L2 (m m)	L3 (m m)	L4 (m m)	L5 (m m)	L6 (m m)	a (de g)	M <sub>tot</sub> (kg /s)	C <sub>id</sub>	T <sub>EGR</sub> (°K)
3	43	10	N/A	250	250	102	33	N/A	N/A	180	0.4	15	505
4	43	10	N/A	65	435	102	33	N/A	N/A	180	0.4	15	505
6	43	10	N/A	250	250	102	33	N/A	N/A	180	0.3	7	505
7	43	10	N/A	250	250	102	33	N/A	N/A	180	0.3	7	450
9	43	10	64	N/A	N/A	102	N/A	130	140	0	0.4	15	505
10	43	10	64	N/A	N/A	102	N/A	130	140	0	0.4	15	505
11	43	10	64	N/A	N/A	102	N/A	130	140	0	0.4	15	505
12	43	10	64	N/A	N/A	102	N/A	130	140	90	0.4	15	505
13	43	10	64	N/A	N/A	102	N/A	130	140	90	0.4	15	505
14	43	10	64	N/A	N/A	102	N/A	130	140	90	0.4	15	505
15	43	10	64	N/A	N/A	102	N/A	130	140	180	0.4	15	505
16	43	10	64	N/A	N/A	102	N/A	130	140	180	0.4	15	505
17	43	10	64	N/A	N/A	102	N/A	130	140	180	0.4	15	505
18	43	10	64	N/A	N/A	102	N/A	130	140	0	0.4	15	505
19	43	20	64	N/A	N/A	102	N/A	130	140	0	0.4	15	505
20	43	20	64	N/A	N/A	102	N/A	130	140	0	0.4	15	505
21	43	20	64	N/A	N/A	102	N/A	130	140	180	0.4	15	505
22	43	20	64	N/A	N/A	102	N/A	130	140	180	0.4	15	505
23	43	20	64	N/A	N/A	102	N/A	130	140	180	0.4	15	505
24	43	10	64	N/A	N/A	102	N/A	130	140	180	0.7	15	505
25*	29	7	43	N/A	N/A	68	N/A	87	93	180	0.4	15	505
26*	64	15	96	N/A	N/A	152	N/A	195	210	180	0.4	15	505
27	43	10	64	N/A	N/A	102	N/A	130	140	180	0.4	21	505
28	43	10	64	N/A	N/A	102	N/A	130	140	180	0.4	15	355
29	43	10	64	N/A	N/A	102	N/A	130	140	0	0.4	15	355
30	34	10	60	N/A	N/A	102	N/A	130	140	180	0.4	21	505
31	51	4	69	N/A	N/A	102	N/A	130	140	180	0.4	15	505
32	51	4	69	N/A	N/A	102	N/A	130	140	180	0.4	21	505
33	51	4	69	N/A	N/A	102	N/A	130	140	180	0.5	34	505
34	51	4	69	N/A	N/A	102	N/A	130	140	0	0.4	15	505
35	51	4	69	N/A	N/A	102	N/A	130	140	0	0.5	34	505
36	51	4	69	N/A	N/A	102	N/A	130	140	90	0.4	15	505
37	51	4	69	N/A	N/A	102	N/A	130	140	90	0.5	34	505
38	51	4	69	N/A	N/A	102	N/A	130	140	0	0.4	15	355
39	51	4	69	N/A	N/A	102	N/A	130	140	0	0.5	34	355

\*For cases 25 and 26 all linear parameters scale by factor 3/2 and 1.5 respectively

## II. SUMMARY OF RESULTS

The following quantities are calculated on sections A-A, B-B, C-C, D-D and the outlet:

$$\sigma_f = ((\int \rho u_n (c_{Act} - c_{id})^2 dA) / \int \rho u_n dA)^{1/2} \quad (1)$$

$$\sigma_{fN} = \sigma_f / c_{id} \quad (2)$$

where  $u_n$  is a normal component of velocity to the section surface,  $\rho$  is mixture density,  $c_{Act}$  is the local secondary fluid concentration,  $c_{id}$  is a ratio of secondary fluid flow rate to total flow rate.

$$\sigma_a = ((\int (c_{Act} - c_{av})^2 dA) / A)^{1/2} \quad (3)$$

where  $A$  is an area of section surface

$$c_{av} = (\int c_{Act} dA) / A \quad (4)$$

The reason for examining the long tube geometry is to investigate the influence of the bend of the pipe on the mixing

process in comparison with the straight pipe. The results show a relatively weak dependence of  $\sigma_{fN}$  on EGR % and EGR temperature for long tube cases. These results are presented in Table II.

TABLE II  
EGR – LONG PIPE

Case	section	$\sigma_f\%/\sigma_{fN}$	$\sigma\%$
3	outlet	3.41/0.22	3.49
4	BB	5.34/0.35	5.32
6	outlet	1.39/0.19	1.32
7	outlet	1.35/0.19	1.30

Cases 3 – 4 show effect of bend

Cases 3 and 6 show effect of EGR%

Cases 6 – 7 show effect of temperature

The effect of the EGR device angle can be seen from a comparison of cases in Table VI. Comparing cases 4 (without the bend) and 11, 14, 17 it is easy to see that the bend significantly improve the mixing process for the angles 0 and 180°, but for angle 90° the bend slightly deteriorates the

mixing in comparison with the straight pipe. The same tendency may be seen for different diameter of EGR device with ratio  $h/D = 0.0433$  (cases 33, 35, and 37).

TABLE III  
EGR MIXER – SHORT PIPE  
RESULTS REPORTED ON OUTLET, INFLUENCE OF PARAMETER  $\alpha$

Case	Angle $\alpha$ (°)	$\sigma_f\%/ \sigma_{IN}$	$\sigma_a\%$
11	0	4.21/0.28	4.31
14	90	6.16/0.41	5.96
17	180	3.78/0.25	3.6
35	0	5.9/0.17	5.56
37	90	7.84/0.23	7.95
33	180	6.93/0.20	6.8

Results in Table IV show the influence of the value of clearance height,  $h$ , on the mixing process. It can be seen here (cases 11 and 20 for  $\alpha = 0^\circ$  & cases 17 and 23 for  $\alpha = 180^\circ$ ) that mixing for different  $h$  with different angles ( $0^\circ$  and  $180^\circ$ ) change in different directions

TABLE IV  
EGR MIXER – SHORT PIPE  
RESULTS REPORTED ON OUTLET INFLUENCE OF PARAMETER  $h$

Case	$h/D$	$\sigma_f\%/ \sigma_{IN}$	$\sigma_a\%$
11	0.0984	4.21/0.28	4.31
20	0.1968	3.93/0.26	4.22
17	0.0984	3.78/0.25	3.6
23	0.1968	5.89/0.39	5.61

The results shown in Table V indicate that for the EGR mixer domain with similar geometry (differing only by linear scale) and constant EGR %, the index of mixing  $\sigma_f$  is practically the same for linear scale changes up to 2.25 times.

TABLE V  
RESULTS REPORTED ON OUTLET INFLUENCE OF LINEAR SCALING

Case	Scale	$\sigma_f\%/ \sigma_{IN}$	$\sigma_a\%$
17	1	3.78/0.25	3.58
25	2/3	3.82/0.25	3.62
26	1.5	3.76/0.25	3.58

Table VI presents the results for the EGR mixer domain with similar geometry (differing only by total flow rate) and constant EGR %. The index of mixing  $\sigma_f$  is the same with a change in the flow rate up to 2 times.

The physical explanation of this phenomenon will be given in the discussion results.

It is important to say that, as shown in this observation, the total flow rate has no influence on the mixing process and it is possible to compare other parameters without considering the flow rate.

TABLE VI  
RESULTS REPORTED ON OUTLET, INFLUENCE OF PARAMETER  $M_{TOT}$

Case	$M_{tot}$ (kg/s)	$\sigma_f\%/ \sigma_{IN}$	$\sigma_a\%$
17	0.36	3.78/0.25	3.58
24	0.715	3.82/0.25	3.62

Table VII shows results with different EGR % than in previous cases. For different EGR % the normalized standard

deviation of EGR concentration,  $\sigma_{IN}$ , is a very convenient index for mixing estimation. Comparing the results from cases 17 and 27 with 15% and 21% EGR respectively, one may say that  $\sigma_{IN}$  or mixing is only slightly changed. Cases 17 and 27 have ratio  $D_{ric} / D = 0.42$ ; for cases 32 and 33 -  $D_{ric} / D = 0.504$ .

Comparing results from cases 40 and 41 for new design mixer with 21% and 34.4% EGR respectively, one may say that  $\sigma_{IN}$  or mixing, in contrary to EGR mixing, is significantly changed.

The physical explanation of this phenomenon will be given in discussion of results.

TABLE VII  
RESULTS REPORTED ON OUTLET INFLUENCE OF EGR%

Case	EGR%	$\sigma_f\%/ \sigma_{IN}$	$\sigma_a\%$
17	15.1	3.78/0.25	3.58
27	21	5.62/0.27	5.56
32	21.1	4.43/0.21	5.22
33	34.3	6.93/0.20	6.8

Table VIII shows results for cases with different temperatures. Cases 11 – 29 have a ratio  $D_{ric} / D = 0.42$ ; for cases 34 – 39  $D_{ric} / D = 0.504$ . It should be emphasized that temperature changes influence the mixing index,  $\sigma_{IN}$ , for different angles ( $0^\circ$  and  $180^\circ$ ) of EGR device (cases 11, 29 and 17, 28).

The physical explanation of this phenomenon will be given in discussion of results.

TABLE VIII  
RESULTS REPORTED ON OUTLET INFLUENCE OF TEMPERATURE

Case	Temperature EGR	$\sigma_f\%/ \sigma_{IN}$	$\sigma_a\%$
17	505	3.78/0.25	3.58
28	355	4.84/0.32	4.67
11	505	4.21/0.28	4.31
29	355	3.96/0.26	4
34	505	3.65/0.24	3.88
38	355	3.73/0.25	3.92
35	505	5.9/0.17	5.56
39	355	5.48/0.16	5.44

Table IX presents results with different ratio  $D_{ric} / D$ . The interesting result here is the significantly increasing  $\sigma_{IN}$ , or decreasing mixing, for case 30 ( $D_{ric} / D = 0.34$ ) in comparison with case 27 where this ratio is 0.42

TABLE IX  
EGR MIXER – SHORT PIPE  
RESULTS REPORTED ON OUTLET INFLUENCE OF PARAMETER  $D_{RIC} / D$

Case	$\sigma_f\%/ \sigma_{IN}$	$\sigma_a\%$
30	12.2/0.58	12.7
27	5.62/0.27	5.56

Table X presents results on outlet for two pipes mixer of water-urea mixture.

$M_{\text{tot}}$ (kg/s)	$\sigma_i$ %	$\sigma_{BN}$
8	6.29	0.25
4	5.97	0.24
2	5.10	0.20

The concentration distribution,  $C$ , obtained from the diffusion equation in this case, has to be a function of non-dimensional parameters  $\mathbf{r}/l$  and, the turbulent Peclet number,  $Pe_t = Ul/D_t$ :

Comparing the results from Table IV for different  $h$ , it is easy to see the results of mixing for different angles ( $0^\circ$  and

Apparently, this effect is caused by higher shear stress in the shear layer between air and EGR flows, which may increase  $D_i$ . The result of case 27 may be explained by the influence of two factors: first is a higher shear stress and second is significantly thinner cold flow layer near the inner radius wall of the elbow. Evidently, in this case, the second effect prevails.

Fig. 2 Schematic of EGR Geometry (Short Tube)

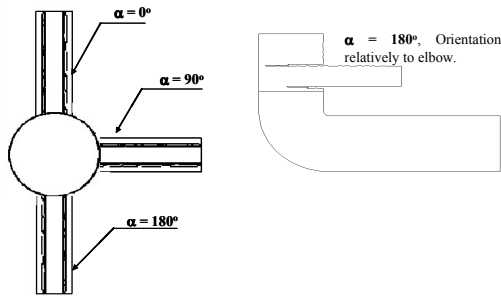


Fig. 3 Definition of EGR Angle

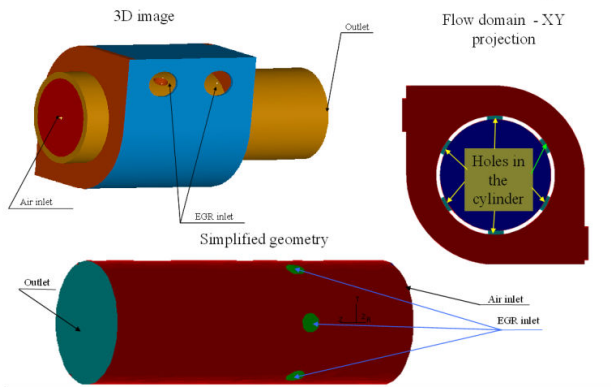


Fig. 4 EGR Mixer Geometries

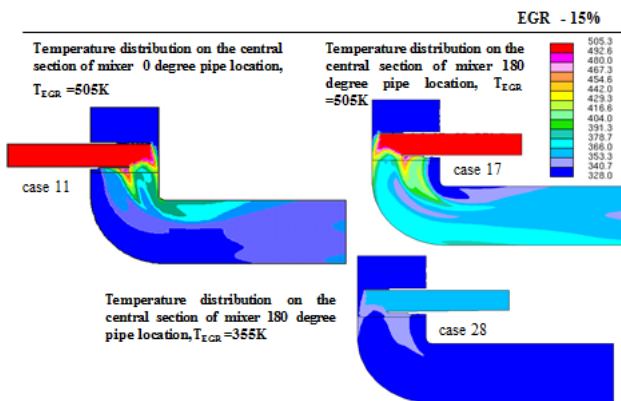


Fig. 5 EGR mixer – Temperature distribution on the central section

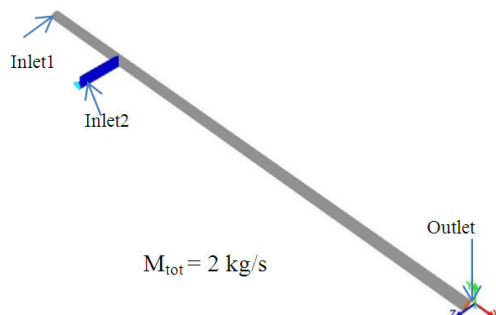
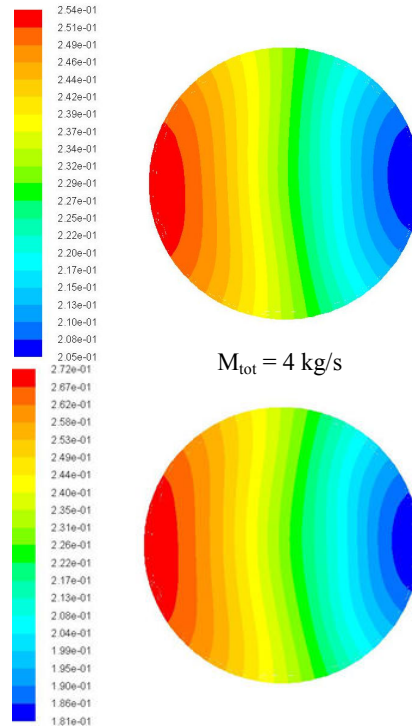


Fig. 6 Geometry of 2 pipes mixer

Fig. 7  $C_{Act}$  on 2 pipes mixer outlet

## IV. CONCLUSIONS

For EGR mixer with a bend the angle for Ricardo device location should be  $0^\circ$  or  $180^\circ$ .

For the EGR mixer the ratio  $D_{ric}/D$  should be 0.4 – 0.5.

This is achievable by using step geometry, impinging flow EGR on a wall, or EGR jets, with a strong change in the flow direction, or using swirler like flow in the domain or combination all of these factors.

The best way to improve the mixing is to establish geometry with the lowest  $Pe_t$  number possible by intensifying the turbulence in the domain.

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