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=const and concentration of secondary fluid ~ 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 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_{act} Concentration of secondary fluid
- c_{id} Ratio of secondary fluid flow rate to total flow rate
- D Pipe Diameter
- D_{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_{tot} Total Flow Rate
- P_{air} Pressure at Air Inlet
- P_{EGR} Pressure at EGR Inlet
- R1 Inner Radius of Elbow
- R2 Outer Radius of Elbow
- T_{air} Air Temperature
- T_{EGR} EGR Temperature
- \alpha Angle of Ricardo Device
- \epsilon Turbulent dissipation rate

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II. SUMMARY OF RESULTS

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

\[
\sigma_f = \frac{\left( \int \rho u_n (c_{\text{Act}} - c_{\text{id}})^2 \, dA \right)}{\left( \int \rho u_n \, dA \right)^{1/2}} \tag{1}
\]

\[
\sigma_{fN} = \frac{\sigma_f}{c_{\text{id}}} \tag{2}
\]

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

\[
\sigma_a = \frac{\left( \int (c_{\text{Act}} - c_{\text{av}})^2 \, dA \right)}{A} \tag{3}
\]

where \( A \) is an area of section surface

\[
c_{\text{av}} = \frac{\int c_{\text{Act}} \, dA}{A} \tag{4}
\]

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.

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).

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° and 180°) change in different directions.

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 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.

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 VII shows results with different EGR % than in previous cases. For different EGR % the normalized standard deviation of EGR concentration, \( \sigma_{EGR} \), 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 \( \sigma_{EGR} \) or mixing is only slightly changed. Cases 17 and 27 have ratio \( D_{ric}/D = 0.42 \); for cases 32 and 33 - \( D_{ric}/D = 0.54 \).

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

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

Table VIII shows results for cases with different temperatures. Cases 11 – 29 have a ratio \( D_{ric}/D = 0.42 \); for cases 34 – 39 \( D_{ric}/D = 0.54 \). It should be emphasized that temperature changes influence the mixing index, \( \sigma_{EGR} \), for different angles (0° and 180°) of EGR device (cases11, 29 and 17, 28).

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

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

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

<table>
<thead>
<tr>
<th>$M_e$ (kg/s)</th>
<th>$\sigma_{in}$</th>
<th>$\sigma_{on}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>6.29</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>5.97</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
<td>5.10</td>
<td>0.20</td>
</tr>
</tbody>
</table>

III. DISCUSSION OF RESULTS

The results shown in Tables VI and X have the following physical explanation.

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, $Pe_t = U_l/D_t$:

$$C = F(\mathbf{r}/l, Pe_t)$$

where $\mathbf{r}$ – is the position vector of the point in the domain in which the concentration is measured (computed), $l$ is a linear scaling factor, $U$ is the characteristic velocity, and $D_t$ is the turbulent diffusion coefficient.

$D_t$ is approximated as $D_t \sim l^2/\varepsilon$, where $k$ and $\varepsilon$ are taken from calculation of the $k$-$\varepsilon$ turbulence model, and $k \sim U_l^2$, $\varepsilon \sim U_l^3/l$.

In this case $Pe_t = const$ and the expression (1) can be rewritten as:

$$C = F(\mathbf{r}/l)$$

In other words, the mixing is practically independent of total flow rate and scale for a given geometry and secondary fluid 5%.

As can be seen in Table III, the bend significantly improves the mixing process for the angles 0 and 180°, but for angle 90°, the bend slightly deteriorates the mixing when compared with the straight tube. There is an explanation of this phenomenon: the recirculation zone responsible for better mixing in the elbow tube has practically no effect on the mixing process, the temperature difference remains low.

The temperature influence on the mixing process for EGR mixer with the long pipe is very weak (cases 5, 6, 7), because in the elbow area, when temperature may influence the mixing process, the temperature difference is relatively low.

For the short pipe, temperature and the clearance between EGR device and tube wall may have some influence on the mixing process.

Table III gives the dependence of mixing on the angle of location of EGR device. The worst case is, as expected, with the angle 90°. The explanation of this phenomenon is shown above.

The 180° location of EGR mixer gives a little bit better result in comparison with 0° location. The physical explanation of this effect will be given later with explanation of temperature effects.

Comparing the results from Table IV for different $h$, it is easy to see the results of mixing for different angles (0° and 180°) change in different directions. It seems that this effect has the same explanation as the previous one.

The influence of EGR temperature on the mixing process of EGR device is presented in Table VIII. It can be seen from Fig. 6, that the best result for mixing is the case where the cold gas is near the small radius of the elbow and hot gas is closer to large radius.

A centrifugal force acting on gas acting on the gas leads, in this case, to a more unstable situation and, as a consequence, to better mixing.

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IV. CONCLUSIONS
For EGR mixer with a bend the angle for Ricardo device location should be 0° or 180°. For the EGR mixer the ratio \( \frac{D_{ric}}{D} \) 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 number possible by intensifying the turbulence in the domain.

REFERENCES