Data Article

Simulation and experimental data resemblance of darmstadt spark ignition engine with different turbulence models – A computational fluid dynamics cold flow data

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**A R T I C L E   I N F O**

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**A B S T R A C T**

The modelling of turbulence for IC engine applications is quite a challenging task. Large Eddy Simulation (LES) is the best approach to model the turbulence as the flow is three dimensional, chaotic, transient, diffusive, dissipative and intermittent. In this paper, a Computational Fluid Dynamics (CFD) data of in-cylinder air movement on TUD (Technische universitat Darmstadt) through Reynolds Average Navier-Stokes (RANS) approach with two different turbulence model, viz. Re-Normalized Group (RNG), K-Epsilon (\( k-\varepsilon \)) and K-Omega (\( k-\omega \)) turbulence models for a single-cylinder, spark-ignition engine is analyzed. A commercial code STAR-CD (Solver for turbulent flow in arbitrary regions-Computational Dynamics) which works based on finite volume method is used for numerical analysis. Qualitative and quantitative data resemblance at a particular crank angle of interest throughout the inlet and compression stroke is analysed. CFD data was compared using the experimental data conducted on a single cylinder engine using a high speed Particle Image Velocimetry (PIV) technique, which was obtained from Darmstadt Technical University. Experimental data from the published literature were difficult to obtain and hence the above data is used for comparison. The resemblance data presented here are in terms of trapped mass of air, in-cylinder pressure,

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Specifications Table

| Subject                          | Mechanical Engineering                        |
|---------------------------------|----------------------------------------------|
| Specific subject area           | In-cylinder air flow measurement during suction and compression stroke in Darmstadt spark ignition engines |
| Type of data                    | Tables, figures                              |
| How data were acquired          | Computer simulation                          |
| Data format                     | Raw, computed, analyzed                      |
| Description of data collection  | The simulation is carried out in STAR CD – 4.22 version, which uses a polyhedral trimmed moving mesh. This RANS simulations are conducted using a workstation with 12 cores and took about 3 days for RNG k-ε and 7 days for k-ω turbulence model for 3 full cycle simulations. In this computation, the suction TDC starts at 360 CAD (Crank Angle Degree) and ends at 540 CAD. Compression starts when piston is at 540 CAD and ends at 720 CAD. The measured variation of pressure at the inlet with crank angle is used for this simulation. The boundary conditions, in terms of pressure 0.95 bar, are specified at the inlet of the intake port, which is located at about 10dp from the neck of the branch [1]. The simulated boundary condition data collected are in steps of 5 CAD from 0 CAD TO 720 CAD. A lengthy duct is included in the model so that the flow conditions at the intake port entrance are appropriate and do not need approximation. This also ensures the correct fluid mass with sensible turbulence level enters the cylinder as the flow evolves through the inlet duct. As stated in the literature [2] the pressure and temperature at the exit of the exhaust duct are specified to be 1.1 bar and 316.7 K respectively. The cylinder walls are specified to be isothermal at 400 K, the piston crown is at 500 K and the cylinder head is at 333 K. The turbulence conditions at the inlet are specified in terms of intensity at 5% and length scale of 0.01 mm. |
| Data source location            | Hopkinson Lab, Cambridge University Engineering Department, UK |
| Data accessibility             | Repository name: Zenodo Repository and Mendeley Data |
|                                 | Data Identification number (permanent identifier, i.e. DOI number): 10.17632/c3pgj4brhh.1 |
|                                 | Direct link to dataset: https://doi.org/10.5281/zenodo.6117269 |
|                                 | https://zenodo.org/record/6117269#.Ymv8X9NBzIU |
|                                 | https://data.mendeley.com/datasets/c3pgj4brhh/1 |

Value of the Data

- This data can be used to predict the number of days needed to run the RANS simulation using two different turbulence model, viz. Re-Normalized Group (RNG), K-Epsilon (k-ε) and K-Omega (k-ω) turbulence models.
- This dataset will be useful for academic researchers attempting to undertake computational fluid dynamics studies in diesel engines.
- This data is more valuable because in-cylinder air motion experimental setup is highly expensive to purchase. Hence, this data can be used as an initial and boundary conditions of CFD simulations.
1. Data Description

The investigated engine configuration (Table 1) is a realistic four stroke Spark Ignited (SI) engine with four poppet valve, pentroof cylinder head, flat piston and two intake and exhaust port which is shown in Fig. 1. Table 2 shows the simulated data of first cycle pressure boundary condition which is given as an input in the form of table format for second and third cycle simulation. The valve lift data is an important parameter to conduct the simulation which is available in Fig. 2.

The good quality of moving mesh generation in STAR-CD to perform an engine simulation is quite a challenging task. In this study, a new automatic mesh generation method was used to generate a three different polyhedral trimmed mesh sizes. When the piston is at BDC, the created mesh comprises of 0.2, 0.4, and 0.8 million cells (Fig. 3) in this study, and this grid independence study was carried out by applying RNG $k-\varepsilon$ turbulence model to figure out the best mesh size and to acquire a higher accuracy of findings when compared to experimental data.

Fig. 4a-c depicts a resemblance data of the in-cylinder flow velocity pattern for three different mesh sizes at the cylinder’s centre plane. Visual study of Fig. 4b and c shows that there is a clockwise (CW) vortex structure inside the cylinder for 0.4 and 0.8 million cells, but it is absent for 0.2 million cells (Fig. 4a). For 0.4 million mesh, the CW vortex is in the middle of the cylinder, whereas for 0.8 million mesh, it is on the right hand side of the cylinder block. Another important observation is that the 0.4 and 0.8 million mesh size are predicting almost the same in-cylinder velocity of 6.9 and 7.3 m/s.

Fig. 5 depicts the data variation of average velocity superimposed over an in-cylinder flow pattern at various crank angle degrees in the cylinder’s mid-plane. Based on this graph, it is clear that 0.4 and 0.8 million cells exhibit a similar pattern with a 7 percent error margin. Fig. 6 shows the resemblance data of mass of air versus CAD. The PIV experiments’ recorded pressure versus time dependent boundary conditions are used as computational input to confirm that the in-cylinder mass of air and pressure standards match the experimental findings. Fig. 7 shows the resemblance of in-cylinder pressure versus CAD. From Fig. 6 and Fig. 7, it is clearly seen that RNG $k-\varepsilon$ and $k-\omega$ turbulence models find the similar trapped in-cylinder mass of air as $480 \times 10^6$ kg after the intake valve closes at 126 CAD bTDC and an in-cylinder peak pressure as 13 bar at compression TDC (at 720 CAD) as compared to experimental results.

Fig. 8 illustrates the comparison of experimental and computed average velocity data of various crank angle degrees from intake to exhaust stroke within the combustion chamber. The graph clearly shows that the maximum velocity is reached at 450 CAD and steadily drops until the end of the compression stroke. The graphical figure also shows that the RNG $k-\varepsilon$ turbulence model under-predicts at the start of the intake stroke and at the end of the expansion stroke. However, $k-\omega$ the turbulence model agrees well with observed average velocity and predicts with more accuracy than the K-epsilon turbulence model.

| Table 1 |
| Engine Specifications. |
|---|---|
| Bore (mm) | 86 |
| Stroke (mm) | 86 |
| Clearance height (mm) | 2.6 |
| Connecting rod length (mm) | 148 |
| Engine Speed (rpm) | 800 |
| Compression Ratio | 8.5 |
| Opening of the Intake Valve (CAD) | 34° before TDC |
| Closing of the Intake Valve (CAD) | 126° before TDC |
| Opening of the Exhaust Valve (CAD) | 106° after TDC |
| Closing of the Exhaust Valve (CAD) | 14° after TDC |
| Intake/exhaust port diameter, $d_p$ (mm) | 60 |
| Intake and exhaust port length (mm) | 10$d_p$ and 7$d_p$ |
Fig. 1. Assembled geometry of an optical engine.
Table 2
Pressure Boundary conditions for cylinder, intake port and exhaust port at 800 rpm.

| Crank Angle (deg) | Cylinder Pressure (bar) | Intake Port Pressure (bar) | Exhaust Port Pressure (bar) |
|-------------------|-------------------------|-----------------------------|-----------------------------|
| 0                 | 0.970151                | 0.969624                    | 0.993725                    |
| 5                 | 0.959293                | 0.974324                    | 1.005232                    |
| 10                | 0.952213                | 0.97542                      | 1.019574                    |
| 15                | 0.951394                | 0.96677                      | 1.026317                    |
| 20                | 0.945599                | 0.95739                      | 1.025882                    |
| 25                | 0.938701                | 0.948                        | 1.019565                    |
| 30                | 0.930997                | 0.937872                    | 1.006435                    |
| 35                | 0.922927                | 0.927945                    | 0.99464                     |
| 40                | 0.918865                | 0.917315                    | 0.981614                    |
| 45                | 0.913744                | 0.912456                    | 0.978911                    |
| 50                | 0.90858                 | 0.914689                    | 0.978911                    |
| 55                | 0.91453                 | 0.915478                    | 0.98648                     |
| 60                | 0.928675                | 0.919055                    | 0.998589                    |
| 65                | 0.932402                | 0.926476                    | 1.009098                    |
| 70                | 0.938016                | 0.938854                    | 1.019594                    |
| 75                | 0.943404                | 0.94852                     | 1.021026                    |
| 80                | 0.951166                | 0.9563                      | 1.017983                    |
| 85                | 0.957356                | 0.964388                    | 1.009242                    |
| 90                | 0.96232                 | 0.97093                     | 0.997603                    |
| 95                | 0.965946                | 0.971099                    | 0.979841                    |
| 100               | 0.967433                | 0.974835                    | 0.980189                    |
| 105               | 0.965906                | 0.971099                    | 0.979841                    |
| 110               | 0.961899                | 0.967307                    | 0.98407                     |
| 115               | 0.95428                 | 0.962744                    | 0.992743                    |
| 120               | 0.94754                 | 0.957139                    | 1.00265                     |
| 125               | 0.944939                | 0.947944                    | 1.01088                     |
| 130               | 0.941679                | 0.940001                    | 1.016261                    |
| 135               | 0.936996                | 0.934929                    | 1.014479                    |
| 140               | 0.934192                | 0.931646                    | 1.0093                      |
| 145               | 0.931396                | 0.93042                     | 0.999796                    |
| 150               | 0.931556                | 0.929039                    | 0.990345                    |
| 155               | 0.933502                | 0.930381                    | 0.983512                    |
| 160               | 0.937024                | 0.934632                    | 0.979594                    |
| 165               | 0.941311                | 0.939416                    | 0.982584                    |
| 170               | 0.948013                | 0.94427                     | 0.987694                    |
| 175               | 0.954575                | 0.948316                    | 0.996414                    |
| 180               | 0.95827                 | 0.953581                    | 1.003948                    |
| 185               | 0.959593                | 0.959494                    | 1.00931                     |
| 190               | 0.96153                 | 0.963924                    | 1.011706                    |
| 195               | 0.962315                | 0.966006                    | 1.008179                    |
| 200               | 0.96436                 | 0.964675                    | 1.002476                    |
| 205               | 0.964816                | 0.963351                    | 0.993515                    |
| 210               | 0.964144                | 0.961258                    | 0.986829                    |
| 215               | 0.965272                | 0.957387                    | 0.982226                    |
| 220               | 0.971521                | 0.95077                     | 0.98148                     |
| 225               | 0.989604                | 0.94104                     | 0.985384                    |
| 230               | 1.018094                | 0.929532                    | 0.991278                    |
| 235               | 1.055139                | 0.919066                    | 0.998878                    |
| 240               | 1.101079                | 0.912145                    | 1.004298                    |
| 245               | 1.156886                | 0.909552                    | 1.007982                    |
| 250               | 1.221618                | 0.908829                    | 1.00761                     |
| 255               | 1.297288                | 0.911879                    | 1.002897                    |
| 260               | 1.385282                | 0.919226                    | 0.996859                    |
| 265               | 1.491906                | 0.931129                    | 0.989398                    |
| 270               | 1.614744                | 0.944105                    | 0.984574                    |
| 275               | 1.761862                | 0.955916                    | 0.98189                     |
| 280               | 1.937976                | 0.966984                    | 0.983359                    |
| 285               | 2.146411                | 0.973904                    | 0.98831                     |
| 290               | 2.396755                | 0.975851                    | 0.994098                    |
(continued on next page)
| Crank Angle (deg) | Cylinder Pressure (bar) | Intake Port Pressure (bar) | Exhaust Port Pressure (bar) |
|------------------|-------------------------|---------------------------|---------------------------|
| 295              | 2.70003                 | 0.975624                  | 1.000371                  |
| 300              | 3.066154                | 0.972925                  | 1.003648                  |
| 305              | 3.511667                | 0.965834                  | 1.004944                  |
| 310              | 4.054714                | 0.956078                  | 1.001871                  |
| 315              | 4.716206                | 0.944311                  | 0.996421                  |
| 320              | 5.5156                  | 0.933995                  | 0.990343                  |
| 325              | 6.466239                | 0.925894                  | 0.984516                  |
| 330              | 7.59296                 | 0.920595                  | 0.981951                  |
| 335              | 8.830069                | 0.92345                   | 0.985795                  |
| 340              | 10.15734                | 0.9291                    | 0.98795                   |
| 345              | 11.44371                | 0.927358                  | 0.990823                  |
| 350              | 12.51641                | 0.934334                  | 0.994626                  |
| 355              | 13.17932                | 0.944339                  | 1.000454                  |
| 360              | 13.28634                | 0.954966                  | 1.001296                  |
| 365              | 12.80427                | 0.963806                  | 1.000149                  |
| 370              | 11.81696                | 0.970461                  | 0.994751                  |
| 375              | 10.52616                | 0.97358                   | 0.990096                  |
| 380              | 9.133344                | 0.972301                  | 0.98483                   |
| 385              | 7.796196                | 0.968481                  | 0.98265                   |
| 390              | 6.597275                | 0.962916                  | 0.982659                  |
| 395              | 5.575259                | 0.955779                  | 0.98459                   |
| 400              | 4.721285                | 0.94696                   | 0.989594                  |
| 405              | 4.021431                | 0.937687                  | 0.994178                  |
| 410              | 3.451115                | 0.930106                  | 0.998351                  |
| 415              | 2.986324                | 0.926246                  | 0.999538                  |
| 420              | 2.609484                | 0.924605                  | 0.998405                  |
| 425              | 2.298675                | 0.926921                  | 0.995449                  |
| 430              | 2.041464                | 0.932586                  | 0.990642                  |
| 435              | 1.829426                | 0.938913                  | 0.986324                  |
| 440              | 1.651855                | 0.946506                  | 0.982861                  |
| 445              | 1.506456                | 0.955211                  | 0.982296                  |
| 450              | 1.382262                | 0.96355                   | 0.983781                  |
| 455              | 1.280581                | 0.970544                  | 0.987355                  |
| 460              | 1.189165                | 0.97496                   | 0.99179                   |
| 465              | 1.116359                | 0.975759                  | 0.995159                  |
| 470              | 1.052157                | 0.973635                  | 0.997251                  |
| 475              | 0.998761                | 0.968641                  | 0.99673                   |
| 480              | 0.952361                | 0.961872                  | 0.994898                  |
| 485              | 0.913124                | 0.955059                  | 0.991009                  |
| 490              | 0.882754                | 0.947809                  | 0.986594                  |
| 495              | 0.862828                | 0.94047                   | 0.979138                  |
| 500              | 0.874316                | 0.934297                  | 0.969045                  |
| 505              | 0.90138                 | 0.931316                  | 0.959257                  |
| 510              | 0.93439                 | 0.931125                  | 0.953281                  |
| 515              | 0.963585                | 0.933609                  | 0.958542                  |
| 520              | 0.985861                | 0.938959                  | 0.974738                  |
| 525              | 1.005051                | 0.945729                  | 0.996309                  |
| 530              | 1.02187                 | 0.952461                  | 1.014124                  |
| 535              | 1.038552                | 0.959339                  | 1.024442                  |
| 540              | 1.049776                | 0.965609                  | 1.026184                  |
| 545              | 1.048564                | 0.970853                  | 1.020409                  |
| 550              | 1.033936                | 0.974214                  | 1.012427                  |
| 555              | 1.009132                | 0.974084                  | 1.001647                  |
| 560              | 0.984684                | 0.971431                  | 0.987686                  |
| 565              | 0.966496                | 0.966687                  | 0.97171                   |
| 570              | 0.957121                | 0.960075                  | 0.958451                  |
| 575              | 0.950772                | 0.953224                  | 0.953481                  |
| 580              | 0.948725                | 0.947183                  | 0.957701                  |
| 585              | 0.955838                | 0.941685                  | 0.968388                  |
| 590              | 0.972968                | 0.937198                  | 0.981035                  |

(continued on next page)
Table 2 (continued)

| Crank Angle (deg) | Cylinder Pressure (bar) | Intake Port Pressure (bar) | Exhaust Port Pressure (bar) |
|-------------------|-------------------------|---------------------------|-----------------------------|
| 595               | 1.000969                | 0.935074                  | 0.992768                    |
| 600               | 1.023572                | 0.93551                   | 1.005992                    |
| 605               | 1.036381                | 0.938676                  | 1.016066                    |
| 610               | 1.037904                | 0.943911                  | 1.027964                    |
| 615               | 1.033237                | 0.950471                  | 1.027483                    |
| 620               | 1.026991                | 0.957519                  | 1.017499                    |
| 625               | 1.0145                  | 0.963629                  | 1.002667                    |
| 630               | 0.994646                | 0.968808                  | 0.98882                     |
| 635               | 0.969398                | 0.972596                  | 0.977335                    |
| 640               | 0.955335                | 0.975025                  | 0.968611                    |
| 645               | 0.953993                | 0.974875                  | 0.965055                    |
| 650               | 0.963946                | 0.971862                  | 0.968198                    |
| 655               | 0.976486                | 0.967185                  | 0.9798                      |
| 660               | 0.98952                 | 0.961291                  | 0.996495                    |
| 665               | 1.006915                | 0.954915                  | 1.011511                    |
| 670               | 1.024251                | 0.949543                  | 1.021701                    |
| 675               | 1.029674                | 0.945533                  | 1.026677                    |
| 680               | 1.02117                 | 0.942605                  | 1.023176                    |
| 685               | 1.006879                | 0.94164                   | 1.011945                    |
| 690               | 0.990485                | 0.942337                  | 0.997309                    |
| 695               | 0.97587                 | 0.945283                  | 0.982127                    |
| 700               | 0.962374                | 0.95025                   | 0.971121                    |
| 705               | 0.953315                | 0.95571                   | 0.967149                    |
| 710               | 0.95886                 | 0.961395                  | 0.970448                    |
| 715               | 0.96744                 | 0.966176                  | 0.980549                    |
| 720               | 0.97081                 | 0.969155                  | 0.992546                    |

Fig. 2. Intake and Exhaust Valve lift Data.
Fig. 3. Variation of Mesh Sizes from 0.2 to 0.8 million cells.

Fig. 4. Resemblance of in-cylinder velocity vector data for three different mesh sizes during compression stroke @630 CAD.

Fig. 9 shows the resemblance of experimental and computational in-cylinder Velocity during intake and compression stroke. The left column of the figure explains the in-cylinder flow pattern during the suction stroke at 450 CAD using RNG $k-\varepsilon$ and $k-\omega$ turbulence model. The right column of the figure illustrates the in-cylinder flow characteristics during the compression stroke at 630 CAD using the above mentioned turbulence models.

Fig. 10 shows the position of measurements on cylinder plane. The RANS approach computational analyses are further extended to study the average velocity, comparison of flow structure and spatial velocities at different locations of $x = 0$, 10, 20 and 30 mm during the intake and compression stroke and compared with an experimental results available from the TUD engine geometry.

Fig. 11 depicts the resemblance of Spatial Velocity during Intake Stroke at 450 CAD. The figure clearly shows that the flow directions are in upward direction for positive velocity and downwards for negative velocity. The expected findings of the RNG $k-\varepsilon$ and $k-\omega$ turbulence models accord well with the data from the PIV experiment.

Fig. 12 shows the resemblance of Spatial Velocity during Compression Stroke at 630 CAD. From Fig. 12, it is seen for both $U_{avg}$ and $V_{avg}$, RNG $k-\varepsilon$ turbulence model over predicts and $k-\omega$ turbulence model under predicts as compared to measured data. The computational results, on the other hand, are in good agreement with the investigative data.
Fig. 5. Data variation of average velocity Vs CAD.

Fig. 6. Resemblance data of mass of air Vs CAD.
Fig. 7. Resemblance data of in-cylinder pressure Vs CAD.

Fig. 8. Resemblance data of average velocity Vs CAD.
Fig. 9. Resemblance data of Experimental and Computational in-cylinder Velocity during intake and compression stroke.
Fig. 10. Position of Measurements on cylinder plane.
Fig. 11. Resemblance data of Spatial Velocity during Intake Stroke at 450 CAD.
Fig. 12. Resemblance data of Spatial Velocity during Compression Stroke at 630 CAD.
2. Experimental Design, Materials and Methods

The computational data of the TUD optical SIDI (spark ignited direct injection) engine geometry are compared with the experimental data of TUD geometry [2]. The experiments were carried out on a single cylinder, spark-ignition engine with an overhead valve pentroof cylinder head and motored at 800 rpm, using an HS-PIV (High speed particle image velocimetry) technique to visualize the in-cylinder velocity and vortex structure during the intake (450 CAD) and compression stroke (630 CAD). The cylinder liner was raised to a height and thickness of 55 × 20 mm in the detailed exploration of PIV technology by installing a transparent quartz glass liner for an optical access of the fire deck combustion chamber and it works as an interrogation window to view the flow [1,2]. As a result, during the post-processing of computational findings to validate the data [3–9], the identical 55 mm cut piece from the cylinder head is used. The four positions of planes are taken for measurements. The measurements planes in experiment are in radial direction and similarly positioned from the cylinder central axis. The four measurement position of planes are at x = 0, 10, 20, 30 mm, which are selected from the available experimental data. Same positions are chosen in CFD study to validate the data.

2.1. Computational details

The fluid domain is obtained from the complete built engine block in such a way that the entire surface is closed and there are no duplicate surfaces. The separated engine block surfaces are the cylinder, pentroof head, flat piston, intake and exhaust valves, and intake and exhaust ports. The surfaces are next cleaned with STAR CCM+ 9.06 to ensure that there are no mistakes of free edges, repeated edges, sharp pair of angles, self-intersection, or shell orientation on cells. After cleaning these surfaces, they are assigned as separate components with various shells, as. Finally, it is surface meshed in STAR CCM+ and imported into es-ice for volume mesh generation and moving mesh generation.

In this CFD simulation, an engine is run at 800 rpm with a constant compression ratio of 8.5. The simulation is run for three cycles, with the first cycle findings ignored due to the initial transients, and only minor variations noticed between the second and third cycles. Therefore, only the second cycle results are used after attaining the stabilized results. This RANS simulation took roughly 3 days for RNG k – ε and 7 days for k – ω turbulence model for three complete cycle runs on a machine with 12 cores. The convective fluxes present in the momentum equations are solved using the monotonic advection reconstruction scheme (MARS), and the Arbitrary Langrangian-Eulerian (ALE) approach is used to discretize the governing equations involved in moving mesh. The pressure coupled velocity equations were solved using the PISO technique.

2.2. Governing equation

The momentum and mass equations solved in Cartesian tensor form for the unsteady, incompressible/compressible, three-dimensional in-cylinder flow [5] are represented as

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = s_m
\]  (1)

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j - \tau_{ij}) = -\frac{\partial p}{\partial x_i} + s_i
\]  (2)

where, t – time, \(x_j\) - Cartesian coordinate \((j = 1, 2, 3)\), \(u_i\) - Absolute fluid velocity component in x-direction, piezometric pressure = \(p_s - \rho_0 g_m x_m\) where \(p_s\) is static pressure, \(\rho_0\) is reference density, \(g_m\) are gravitational acceleration components and \(x_m\) are coordinates relative to a datum
where $\rho_0$ is defined as Density, $\rho$

$$\rho = \left(\frac{p}{RT \sum \frac{m_m}{M_m}}\right)$$

where $m_m$ - mass fraction of a constituent with molecular weight $M_m$, $T$ - temperature, $R$ - universal gas constant, $\tau_{ij}$ - stress tensor components, $S_{ij}$ - mass source, $S_i$ - momentum source components (assumed to be negligible). Assuming Newtonian flow, the following constitutive relation is stated to relate the components of the stress tensor $\tau_{ij}$ to the velocity gradients:

$$\tau_{ij} = 2\mu s_{ij} - 2\frac{\mu}{3} \frac{\partial u_k}{\partial x_i} \delta_{ij} - \rho \omega_i \omega_j$$  \hspace{1cm} (3)$$

Where $\mu$ - molecular dynamic fluid viscosity, $\delta_{ij}$ - the Kronecker delta ($= 1$ when $i = j$, and 0 otherwise)

$$s_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$  \hspace{1cm} (4)$$

The fluctuations about the ensemble average velocity are represented by the rightmost component in Eq. (3), which reflects the increased Reynolds stresses owing to turbulent motion. Through turbulent models, the Reynolds stresses are related to the mean velocity fields.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Data Availability**

TUD Boundary Condition (Original data) (Boundary Condition).

**CRediT Author Statement**

A Gnana Sagaya Raj: Conceptualization, Methodology, Software, Validation, Visualization, Supervision, Investigation, Writing – original draft, Writing – review & editing; Chandra Sekhar Mishra: Writing – review & editing.

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