Indian Journal of Engineering & Materials Sciences
Vol. 32, August 2025, pp. 486-492
DOI: 10.56042/ijems.v32i04.18792

Effect of radial jets in exhaust system of spark ignition engine – Exergy analysis

Nilaj Deshmukh[a*], Samir Nimkar[b], Kaustubh Jambhale[a], Rohit Kadam[a], Athul Krishna T.B.[a] & Shantanu Soshte[a]

[a]Department of Mechanical Engineering, Fr. C. Rodrigues Institute of Technology, Vashi, Navi Mumbai 400 708, Maharashtra, India

[b]Department of Chemical Engineering, Bharati Vidyapeeth Institute of Technology, Belapur, Navi Mumbai 400 614, Maharashtra, India

Received: 15 April 2025; accepted: 13 July 2025

This research has examined the effect of radial air injectors on the theoretical exergy of an exhaust system in a Spark Ignition (SI) engine. The radial air injectors have been installed in three different positions along the silencer's bend pipe. Exergy analysis has determined the amount of irreversibility in a process, and its quality, associated with the thermodynamic efficiency of work output. The results of the study have indicated that system efficiency has increased when using radial air injectors. The measurement of exergy destruction with 8 radial jets present has been 0.1679 kWh. With 16 jets, this value has risen to 0.2019 kWh and has increased further to 0.23 kWh with 24 jets. The results of the experiments have been analyzed, and it can be concluded that increasing the quantity of radial jets has had an effect on a system's exergy performance. These results have provided evidence for the advantage of employing radial air injectors in exhaust systems of SI engines to make them more efficient and to decrease their negative environmental effects.

Keywords: Exergy analysis, Exhaust system, Exhaust system optimization, Spark-ignition engine

1 Introduction

The performance of internal combustion engines is significantly influenced by the design and optimization of exhaust systems, particularly the muffler. An exhaust system not only serves to reduce noise emissions but also impacts the overall engine efficiency by managing back pressure and controlling exhaust flow characteristics. Enhanced muffler designs, incorporating advanced flow manipulation techniques, have been shown to improve noise attenuation while also impacting fuel efficiency and emissions[1,2]. Studies indicate that incorporating radial air jets within the muffler may further improve noise control and thermal management, which can directly affect engine performance[2,3].

Exergy analysis is a vital technique for assessing exhaust systems' energy efficiency. A system's usable energy is represented by its energy destruction process, which also reflects the irreversibility, or losses, of that system[4-6]. Extensive research has recently applied exergy analysis to a variety of engineering systems, emphasizing how crucial it is to reduce exergy degradation in order to increase efficiency[7,8]. The exergy analysis has facilitated improvements in system efficiency and sustainability by pinpointing areas of energy dissipation throughout different thermal processes and system studies[9,10,11]. In this research study, exergy analysis will be applied to assess the thermodynamic effects caused by adding radial jets to the muffler configuration.

Radial jets, particularly in the configuration of jets in crossflow, are critical in engineering applications involving high mixing rates, such as in combustion chambers and propulsion systems. Jets in crossflow, wherein fluid is injected at an angle perpendicular to the main flow, create complex vortex structures that enhance mixing and temperature distribution. This phenomenon is particularly relevant in exhaust systems, where introducing radial jets could improve thermal distribution and reduce localized hot spots within the silencer. Enhanced cooling through radial jets can contribute to a more uniform temperature profile, potentially reducing thermal stress and emissions from the exhaust system.

For this paper, a simulation model was made with reference to an experimental setup and the data was processes using Ansys Software to understand the effect of radial air injectors on the temperature. The systems exergy destruction was calculated using analytical methods under different configurations of

*Corresponding author (E-mail: nilaj.deshmukh@fcrit.ac.in)

radial air injectors. When 8 radial jets were active, the exergy destruction was 0.1679 kWh. With 16 jets, the exergy destruction increased to 0.2019 kWh. When all 24 jets were operational, the exergy destruction reached 0.23 kWh. Based on the data, comments were made on the efficiency of each system on thermodynamic parameters as well as over the emission rates in the system.

1.1 Terminology

The energy balance of the system shows input energy is the sum of output energy and accumulation. This is not true for exergy balance because some part of exergy is lost in the process. Exergy is the availability of energy in provided resource and its value depends upon reference environment. Physical exergy is the work obtained when the system is brought from its original state to environmental state. Total exergy (E) of a closed system is the combination of physical, kinetic, potential, and chemical exergy and can be expressed as[3,12,13],

$$E = E^{PH} + E^{KN} + E^{PT} + E^{CH} \quad \text{... (1)}$$

Where E stands for Exergy, PH stands for Physical Exergy, Physical Exergy, KN stands for Kinetic Exergy, PT stands for Potential Exergy and CH stands for Chemical Exergy of flowing stream is written as[3,12,13],

$$E = (H - H_0) - T_0(S - S_0) \quad \text{.... (2)}$$

Where H is Enthalpy, S is Entropy and 0 indicate Environmental state.

2 Materials and Methods

2.1 Experimental setup

To conduct experiments, a 100 cc, four-stroke engine from Bajaj CT100 was used. The standard silencer underwent modifications to accommodate radial air injection ports for injecting air radially at three distinct locations. An arrangement featuring 8 ports with air injectors of 1 mm inner diameter and 3 mm outer diameter was positioned at 100 mm, 200 mm, and 300 mm respectively from the inlet end of the silencer pipe. The experimental setup included an engine, silencer, compressor, and radial air jet injection arrangement. Temperature measurements were carried out using K-type thermocouples, composed of chromel-alumel, with an accuracy range of -273 K to 873 K. The data acquisition system comprised of National Instruments' NI USB- 6211 and Lab VIEW software 7.1, serving as the interface between all sensing devices and the computer. The radial air jet arrangement over the silencer is shown in Fig. 1 and the entire experimental setup is shown in Fig. 2.

2.2 Simulation study

For carrying out the simulation study in future CAD design of the silencer has been made. The available silencer was studied, and dimensions were noted. Based on the dimensions the silencer CAD Model was made. The software used to make the Silencer was Autodesk Inventor. Figure 3 shows the actual image of the exhaust system of Pulsar dtsi 150 cc bike as well as its CAD model which depicts the front view of the silencer. The silencer is a reflective type of silencer. The exhaust flue gas from the engine enters the bent pipe of the silencer. This pipe connects to the reflective chamber of

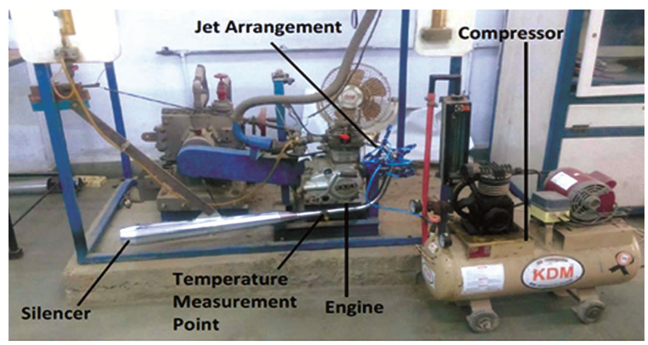

Fig. 1 — Arrangement of radial air injectors.

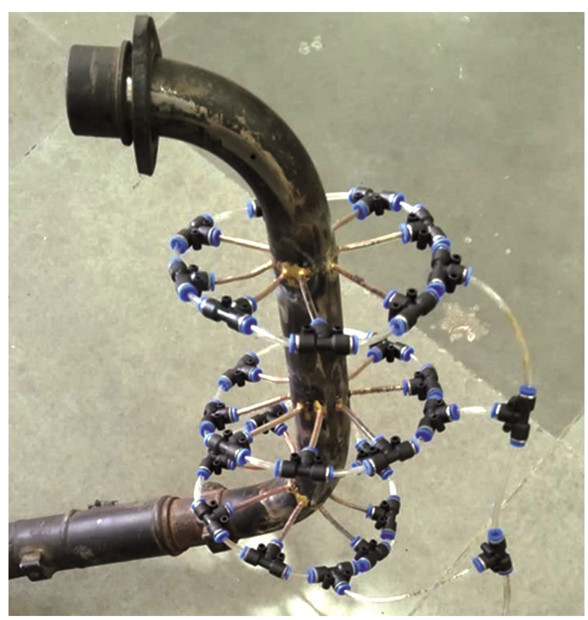

Fig. 2 — Experimental setup.

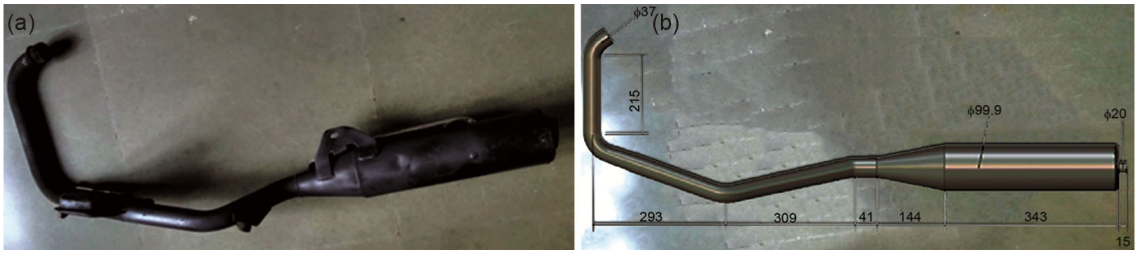

Fig. 3 (a) — Actual image and CAD model of silencer; (b) cross section view of silencer.

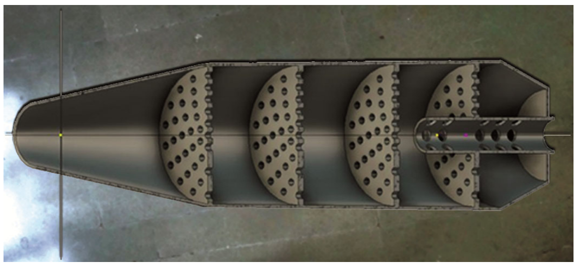

Fig. 4 — Bend Pipe of the silencer with no modification.

Fig. 5 — Modified silencer with 1 set of radial air injectors (8 radial jet injectors) placed at a distance of 100 mm from the silencer end.

silencer. There are 4 reflective chambers in silencer. Figure 4 highlights the sectional front view of the cylinder of the exhaust system. The cylinder is divided into 5 sections by holed circular discs along with tubular section of length 100 mm and diameter 20 mm. Figure 5 displays the side view of the exhaust system showing bend pipe and cylinder of the silencer.

The silencer has been modified as per the experimental setup. The effect of air which is flowing in near perpendicular direction or in cross flow on the exhaust gases flowing inside the silencer is observed. The following cases are considered for the modified silencer. 3 cases based on the silencer positioning were considered.

Case 1: 1 set of radial air injectors (8 radial air injectors) each at 100 mm from the end of the silencer pipe. Figure 6 denotes the arrangement in CAD model.

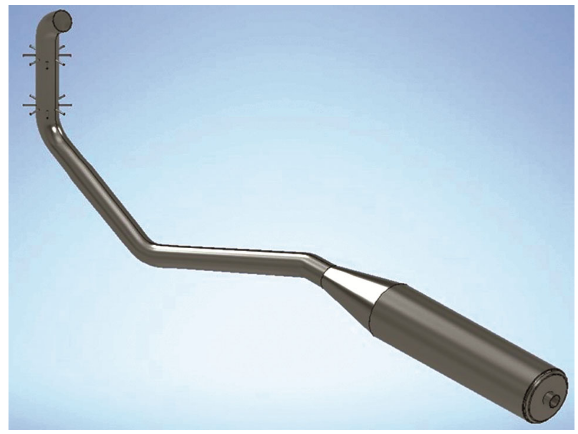

Fig. 6 — Modified silencer with 2 sets of radial air injectors (16 radial jet injectors) placed at a distance of 100 mm and 200 mm from the Silencer end.

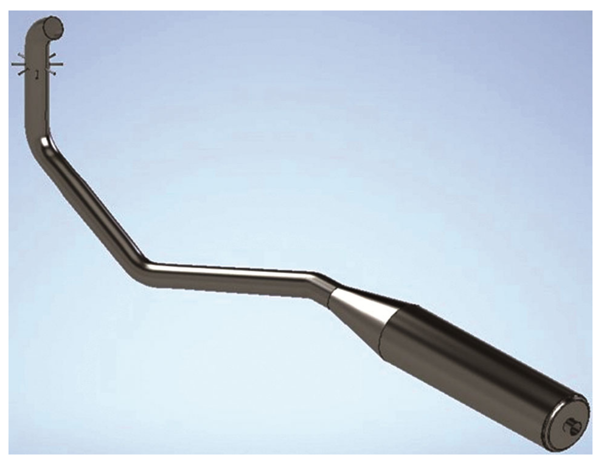

Fig. 7 — Modified silencer with 3 sets of radial air injectors (24 radial jet injectors) placed at a distance of 100 mm, 200 mm and 300mm from the silencer end.

Case 2: 2 sets of radial air injectors (16 radial air injectors), with one set at the same configuration as Case 1, i.e. at 100 mm from the end of the silencer pipe and another set at 200 mm from the end of the silencer pipe. Figure 7 denotes the CAD model of the setup.

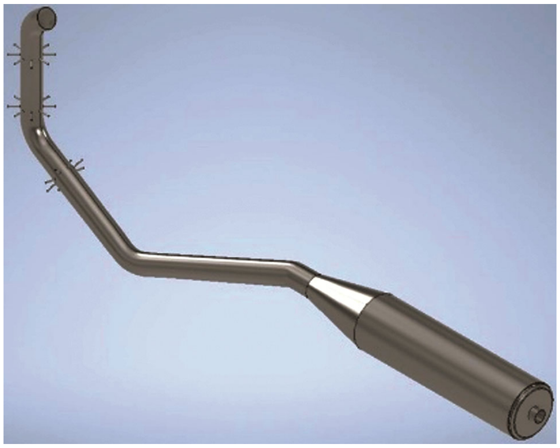

Fig. 8 — Temperature distribution for air injection at first location.

Case 3: 3 sets of radial air injectors (24 radial air injectors) with the 2 sets same as Case 2 and the third set placed at a distance of 300 mm from the end of the silencer pipe. Figure 8 denotes the arrangement in CAD model.

2.3 Simulation Setup

For simulation purposes, the experimental setup was recreated in Ansys® software. The temperature of exhaust gases at the inlet of the silencer is 710 K. Air is injected through the radial air injectors at 3 bar pressure respectively. The temperature of air injected through the radial air injectors is 300 K. The fuel used was CH4 (methane). The reason methane was used over gasoline was, methane undergoes incomplete combustion in Ansys 2022 R1. The simulation done was done in SST k- ε model. K- ε model was used to improve the mixing-length model, as well as to find an alternative to algebraically prescribing turbulent length scales in moderate to high complexity flows. This model was choosen as it performs better in near wall behaviour and turbulent shear stress corrections. The first transported variable is the turbulent kinetic energy (k). Following mass flow rates were considered in input parameters along with temperature and pressure to define rate at which mass is entering the domain. The Inlet Fuel flow rate for combustion was 0.000188 kg/s. The Inlet Airflow rate foe combustion was 0.0036 kg/s. The inlet airflow rate for the radial air injectors was 0.001894 kg/s.

3 Results and Discussion

3.1 Experimental results

Case 1: Air injection at first point i.e., at 100 mm from flue gas inlet to the silencer. As shown in Fig. 9,

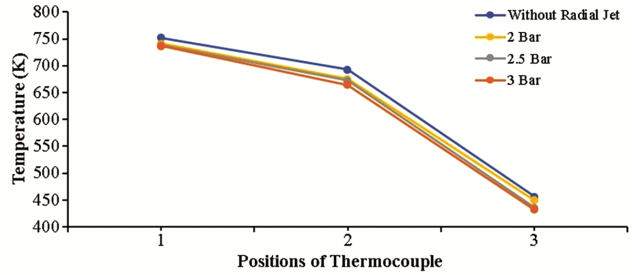

Fig. 9 — Temperature distribution for air injection at first and second location.

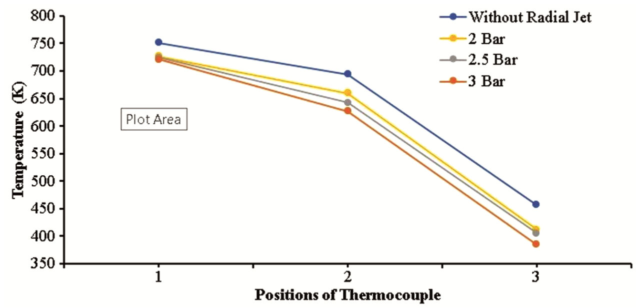

Fig. 10 — Temperature distribution for air injection at all three locations.

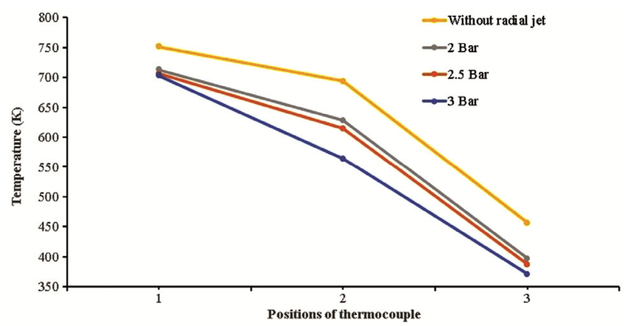

Fig. 11 — Cross sectional temperature contour of the outlet of silencer.

temperature results for air injection at first location shows temperature reduction of 24.595 K for air injected at 3 bars compared to no air injection.

Case 2: Air injection at first point and second point i.e. at 100mm and 200mm from flue gas inlet to the silencer. As shown in Fig. 10, temperature results for air injection at first and second location shows temperature reduction of 72.265 K for air injected at 3 bars compared to no airinjection.

Case 3: Air injection radially at three locations ie 100 mm, 200 mm and 300 mm from the flue gas inlet to the silencer. As shown in the Fig. 11 the temperature results for air injection at first, second and third location shows a temperature reduction of 85.53 K for air injected at 3 bars compared to no air injections.

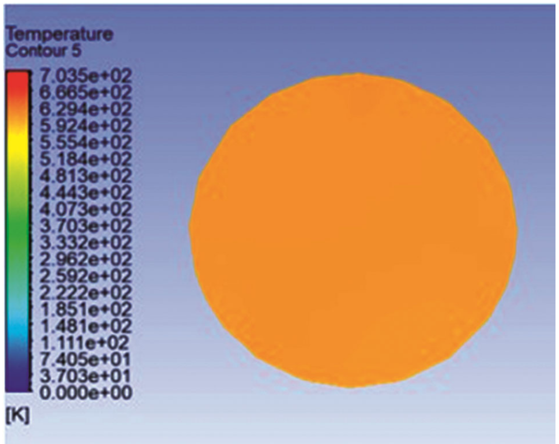

Fig. 12 — Cross sectional temperature contour of the silencer section after interaction of flues gases and air injection at first set.

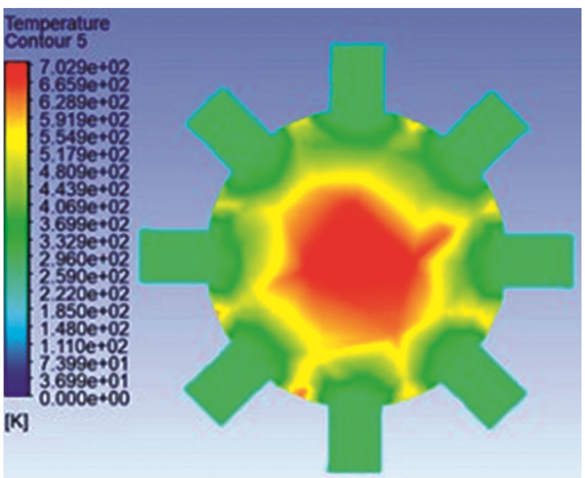

Fig. 13 — Cross sectional temperature contour of the silencer section after interaction of flues gases and air injection at second set.

3.2 Simulation results

When no radial air injectors were engaged, temperature distribution as shown in Fig. 12 is achieved. The overall temperature of the flue gases is constant throughout the cross-section.

Case 1: When radial air injectors positioned at 100 mm were engaged, it was observed that the after the interaction of air with flue gases, there was a temperature drop, and the temperature distribution is shown in the Fig. 13.

Case 2: When radial air injectors at 100 mm and 200 mm were engaged the temperature at the exhaust further drops as shown in Fig. 14.

Case 3: When radial air injectors at 100 mm, 200 mm and 300 mm were engaged the temperature at the exhaust dropped and its temperature distribution is shown in Fig. 15.

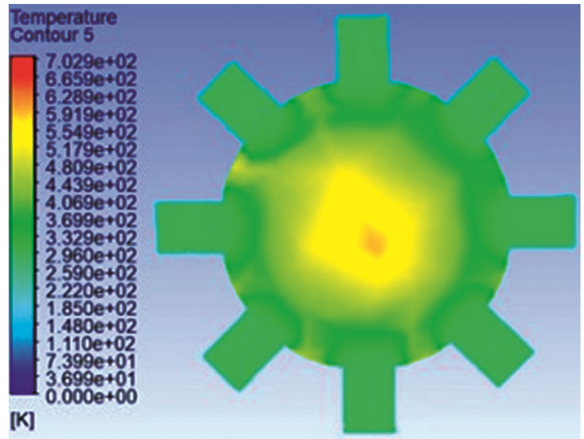

Fig. 14 — Cross sectional temperature contour of the silencer section after interaction of flues gases and air injection at third set.

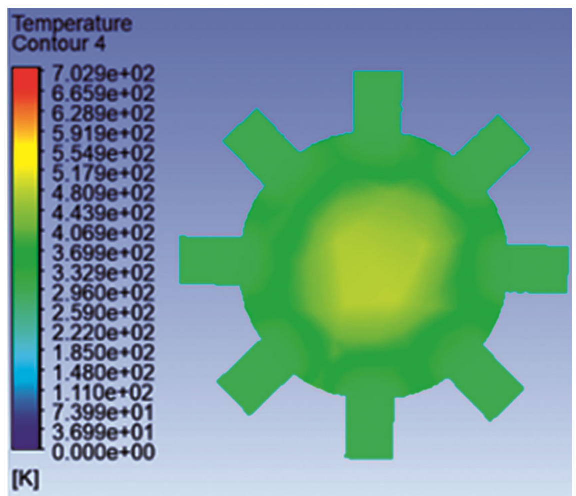

Fig. 15 — Temperature variation along the length of the silencer for 3 bar pressure.

Table 1 — Inlet and Outlet temperatures of silencer for single, double, and triple sets of air injector.

Radial Jet Employment Status	Silencer Inlet Temperature	Silencer Outlet Temperature
No Set Employed	710K	696K
1s t Set Employed	710K	554K
1^{st} and 2^{nd} Set Employed	710K	418K
All 3 sets Employed	710K	332K

The inlet and outlet temperatures of the silencer for all three arrangements of air injections is compared with no air injection in the Table 1. The same can be visualized through Fig. 16.

3.3 Analytical Exergy Results

Table 2 denotes the thermodynamic parameters achieved within the system when the first set of radial

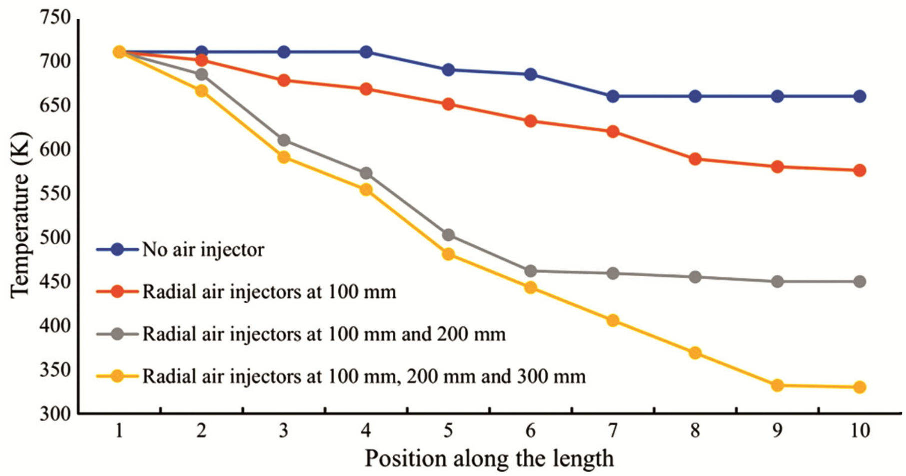

Fig. 16 — Variation in exergy destruction for all 3 arrangements at 3 bars.

Table 2 — Thermo dynamic parametersfor1st set of radial injectors at 3 bar pressure.

Position	T(inK)	P(inbar)	$\dot{m}$ (inkgs^{-1})	h(kJkg^{-1})	s(inkJkg^{-1}K^{-1})	e(inkJkg^{-1})
At silencer inlet	710.00	3	0.0071	463.16	0.9264	186.9513
At first set of radial air injector	300.00	3	0.0101	1.20	-0.3073	92.8151
At outlet of silencer	685.41	2	0.0172	434.51	0.8812	171.7787
At Dead State	298.15	1	-	0	0	0

Table 3 — Thermo dynamic parametersfor1st and 2nd set of radial injectors at 3 bar pressure.

Position	T(inK)	P(inbar)	$\dot{m}$ (inkgs^{-1})	h(kJkg^{-1})	s(inkJkg^{-1}K^{-1})	e(inkJkg^{-1})
At silencer inlet	710.00	3	0.0071	463.16	0.9264	186.95
At first set of radial air injector	300.00	3	0.0101	1.20	−0.3073	92.82
At second set of radial air injector	300.00	3	0.0101	1.20	−0.3073	92.82
At outlet of silencer	637.74	2	0.0273	378.98	0.7936	142.37
At Dead State	298.15	1	-	0	0	0

air injectors were activated, i.e. when 8 radial jets were functioning. The parameters are determined after there is interaction of air and flue gases within the system. Based on these parameters the exergy destruction in the system has been calculated using analytical methods. The amount of exergy destruction in this case is 0.1679 kWh.

Table 3 denotes the thermodynamic parameters achieved within the system when the first and second set of radial air injectors were activated, i.e. when 16 radial jets were functioning. Based on these parameters the exergy destruction in the system has been calculated using analytical methods. The amount of exergy destruction in this case is 0.2019 kWh.

Table 4 denotes the thermodynamic parameters achieved within the system when all three sets of radial air injectors were activated, i.e. when 24 radial jets were functioning. Based on these parameters the exergy destruction in the system has been calculated using analytical methods. The amount of exergy destruction in this case is 0.23 kWh.

The occurrence of a high-speed fluid jet being introduced into a stream that is flowing perpendicularly is known as jets in crossflow. Significant applications of this interaction exist in a few disciplines, including fluid dynamics and engineering. Aerodynamic designs of airplanes, combustion systems, exhaust emissions, and industrial processes like mixing and heat transfer are all influenced by the intricate dynamics of jets in crossflow. Studying the complex interactions between the jet and the surrounding flow, which can result in complex vortices, turbulence, and changes in flow patterns, is necessary to comprehend this

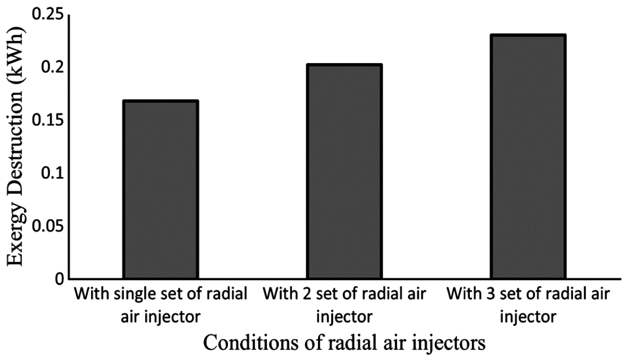

Fig. 17 — Variation in Exergy Destruction for all 3 arrangements at 3 bars.

phenomenon. To improve mixing procedures, maximize combustion efficiency, and boost the functionality of a variety of systems, researchers are constantly studying jets in crossflow.

From these values of exergy destruction, the efficiency of the systems can be known. Exergy destruction is a positive quantity for any actual process. It becomes zero for reversible process. But for an irreversible process, the exergy destruction represents the lost work potential and is also called the irreversibility in work. The amount of exergy destroyed represents the amount of work lost. So, from the values of exergy destruction values, it can be commented that the amount of work potential lost for one set of radial air injectors is the least followed by when two sets of radial air injectors are engaged, and three sets of radial air injectors are engaged.

Figure 17 indicates that the exergy destruction in case of three radial injectors is more than in case of single radial injector which indicates that more energy can be harnessed for useful purposes.

4 Conclusion

This research shows that by including the radial air injectors in the exhaust system of a spark-ignition engine, the efficiency of the system is improved. By analyzing different configurations, it was observed that increasing the number of radial jets improves heat dissipation and alters the thermodynamic behavior of the exhaust system. The results depict that with an increase in radial air injectors, energy utilization in the system increases simultaneously thus contributing to overall system efficiency. It is noted that with an increase in exergy destruction, this is made possible. This approach may help in optimizing the design of the exhaust system by lowering energy losses and minimizing negative impacts on the environment. More detailed studies regarding the optimization of injector position and flow rate could yield important information regarding efficiency and performance enhancement.

References

1 Deshmukh N & Waghmode A, Int J Therm Eng, 9 (2021) 107.
2 Karagozian A R, Prog Energy Combust Sci, 36 (2010) 531.
3 Selvaraj N V & Deshmukh N N, Indian J Sci Technol, 9 (2016) 1.
4 Tsatsaronis G, Energy, 32 (2007) 249.
5 Aygun H, J Therm Eng, 9 (2023) 69.
6 N G, Bhat M M, Akshay L & Arumuga Perumal D, Therm Sci Eng Prog, 8 (2018) 93.
7 Dincer I & Rosen M A, Exergy: Energy, Environment and Sustainable Development, Newnes, 2012.
8 Lagrandeur J, Croquer S, Poncet S & Sorin M, Int J Heat Mass Transf, 152 (2020) 119527.
9 Nimkar S C & Mewada R K, Int J Exergy, 15 (2014) 468.
10 Norouzi N, Ebadi A G, Bozorgian A, Hoseyni S J & Vessally E, Iran J Chem Chem Eng, 40 (2021) 1909.
11 Nimkar S C, Mewada R K & Rosen M A, Int J Hydrogen Energy, 42 (2017) 28113.
12 Balli O, J Therm Eng, 6 (2020) 697.
13 Boominathan N, Kathiravan R & Vijayaraghavan G, Int J Appl Environ Sci, 13 (2018) 669.
14 Agrebi S, Dreßler L & Nishad K, Entropy, 24 (2022) 564.
15 Sezer I & Bilgin A, Int J Exergy, 5 (2008) 204.
16 Şöhret Y, J Therm Eng, 4 (2018) 2083.
17 Durmusoglu Y & Koçak G, J Therm Eng, 5 (2018) 1.
18 Koroglu T & Sogut O, J Therm Eng, 3 (2017) 1136.
19 Ozgur B, Int J Turbo Jet-Engines, 36 (2019) 305.