Experimental investigation of mechanical properties of Acrylonitrile Butadiene Styrene (ABS) based polymer for Submersible pumps

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Abstract. Now a day’s many companies manufacturing the most advanced submersible pumps with Acrylonitrile Butadiene Styrene (ABS) based polymer, which is available in the market for use in domestic, commercial and even research activities. ABS based pumps are widely used in mining, construction and chemical industries. Acrylonitrile Butadiene Styrene has much application in the temperature range from −20 to 80°C. The ABS based polymer composites are used in submersible pumps due their important properties such as corrosion resistance, light weight, erosion resistance, etc. In the current work, the technique used for the fabrication of GFRP- ABS laminate is compression molding, as per the ASTM standard. The various tests are conducted as per Design of Experiments. Analysis of experimental data was performed using Minitab software and tests were conducted for Flexural strength, Inter Laminar Shear Stress, Tensile strength. Three factors are considered for the Design of Experiments namely, fibre-to-resin ratio, fibre orientation and period of immersion in artificial sea water. The outcome points towards Flexural strength; ILSS and Tensile Strength are highest along 40:60 fibre-to-resin ratio with 0°/90° fiber orientation, longer the contact to sea water more is the fall in the strength of the composite material and also due to sea water diffusing into the composite material specimen, there is an increase in its weight.

1. Introduction
Research of ABS Plastic has gained importance from several decades for its significant existence in practical applications and has increased demand nowadays. Adding glass fibre-reinforced composites has much higher strength than ABS material. Several researchers explored explanations for improving the properties of mechanical. Along with clay, the inclusion of glass increases the strength of ABS composites [1]. Better tensile and flexural properties are provided by the use of ABS/PC blend; these properties can be further improved by the addition of Kevlar fibres as reinforcement [2].

The tensile properties of ABS can also be strengthened in the form of short glass fibre/calcite fibre hybrid composites reinforced by ABS[3]. In the case of particle-reinforced ABS composites, the particle size influences the mechanical properties; in a study by L Jiang et al.[4], micron-sized calcium carbonate strengthened the module but decreased the tensile and impact strength, whereas nano-sized...
calcium carbonate displayed an improvement in impact properties along with the modulus. Addition of short glass fibre to ABS lowers the fracture toughness, whereas, addition of short glass fibres to calcite-filled ABS improves the fracture toughness [5]. Addition of a very small content 1 wt% of multi-walled carbon nano tubes improves the yield strength and flexural modulus of polyamide6/ABS blend [6]. Impact strength can be improved by sandwich structural composites; a study showed improved impact properties in CFRP/ABS/CFRP (carbon fibre-reinforced epoxy polymer) composites as compared to ABS [7]. Adding sawdust as reinforcement to ABS improved its modulus with a decrease in strength [8]. Waste textile fibres can also be put to use as a reinforcing material for ABS, this improves flexural properties of ABS [9]. Addition of thermal exfoliated graphite as reinforcement enhances electrical conductivity of ABS [10]. Research of ABS Plastic has gained importance from several decades for its significant existence in practical applications and has increased demand nowadays. Adding glass fibre-reinforced composites has much higher strength than ABS material. Many researchers investigated reasons for improving mechanical properties. Addition of glass along with clay increases the toughness of ABS composites [1]. Using ABS/PC blend gives better tensile and flexural properties; these properties can be further enhanced by the addition of Kevlar fibres as reinforcement [2]. The tensile properties of ABS can also improved in the form of hybrid composites of short glass fibre/calcite fibre reinforced be ABS [3]. In case of particle reinforced ABS composites, size of the particles affects the mechanical properties; micron-sized calcium carbonate improved the modulus but lowered tensile and impact strength, whereas, nano-sized calcium carbonate showed increase in impact properties along with modulus in a study by L Jiang et al. [4]. Addition of short glass fibre to ABS lowers the fracture toughness, whereas, addition of short glass fibres to calcite-filled ABS improves the fracture toughness [5]. Addition of a very small content 1 wt% of multi-walled carbon nano tubes improves the yield strength and flexural modulus of polyamide6/ABS blend [6]. Impact strength can be improved by sandwich structural composites; a study showed improved impact properties in CFRP/ABS/CFRP (carbon fibre-reinforced epoxy polymer) composites as compared to ABS [7]. Adding sawdust as reinforcement to ABS improved its modulus with a decrease in strength [8]. Waste textile fibres can also be put to use as a reinforcing material for ABS, this improves flexural properties of ABS [9]. Addition of thermal exfoliated graphite as reinforcement enhances electrical conductivity of ABS [10-38].

2. Methodology
The Figure 1 Describes the methodology followed for mechanical and abrasive studies respectively to complete the research work, and various tools that were employed at various stages of research.

Fabrication of test specimen
The sheet-shaped test specimens are cut according to the ASTM (ASTM-D638), ILSS (ASTM-D2344), impact test (ASTM-D256), flexural test (ASTM-D790) and flexural fatigue test (ASTM D671-93) specifications, respectively.
Preparing artificial sea water
In a temperature-controlled tank, artificial sea water is formulated according to the ASTM D1141 standard. In order to treat artificial sea water, 250 litres of purified water was used. The amounts of sodium chloride, calcium chloride, magnesium chloride, sodium bicarbonate and sodium carbonate weighted precisely were applied to the purified water in the quantities referred to in Table 1. The artificial sea water was prepared in temperature controlled sea water as shown in Figure 2.
Exhaustive literature survey related to moisture degradation of polymer

Design of experiments by

Fabrication of test specimen  Preparation of artificial sea

Hygrothermal ageing of specimen at constant

Recording change in volume and weight gain of the aged

Conducting Mechanical

Tensile  Inter laminar  Impact  Flexura  Flexural

Taguchi  Analysis of variance  Grey relational

Optimized process

**Figure 1.** Flowchart for the project methodology (Mechanical properties)

Design of Experiments (DoE) 

Minitab V16 software is used to define the DoE with mixed level Taguchi orthogonal array. The array was developed using three factors viz. Period of immersion in artificial sea water with 6 levels (15, 30, 45, 60, 75 and 90 days), fibre-to-resin ratio with 3 levels (60:40, 50:50 and 40:60) and fibre orientation with 3 levels (0°/90°, 45°/45° and 30°/60°).
Figure 2. Temperature controlled tank

Table 1. Composition of artificial sea water

| Sl. No. | Constituent | Quantity (grams) |
|---------|-------------|-----------------|
| 1       | NaCl        | 7597.59         |
| 2       | CaCl₂       | 401.362         |
| 3       | MgCl₂       | 2907.346        |
| 4       | NaHCO₃      | 43.68           |
| 5       | Na₂CO₃      | 5.512           |

3. Results and Discussion

The developed specimens were fabricated for various testing as per their applications. The various testing conducted as per design of experiments. The obtained results are given in this section. Analysis of experimental data was performed using Minitab software and two tests were performed for each factor, i.e. Taguchi analysis and Analysis of Variance (ANOVA) analysis. The factors analysed were, Flexural strength, ILSS, Tensile strength, Impact strength, Swelling and % wt gain and abrasive resistance of the ABS and its composites. The functional properties such as damping, XRD, fracture surface, phase transformation, FTIR and flammability test were presented.

Flexural strength

3-pt bending strength values from the flexural tests were considered for this analysis.

Taguchi analysis

The mean of means and mean of signal-to-noise ratio plots, as shown in, point out highest strength for sample with 40:60 fibre-to-resin ratios with 0o/90o fibre orientation. In addition, longer the contact with artificial sea water further is the lessen in the strength of the composite.

Figure 3 shows weighted mean plots for multiple flexural strength variables. It can be found that the flexural intensity represents a continuously declining tendency as specimen immersion time increases in sea water. For the rising fibre-to-resin ratio, a lessening pattern is seen for flexure strength. And the overall flexural power of the fibre orientation of 0o/90o is followed by 30o/60o & 45o/45o.

The Figure 4 displays the mean of signal to noise ratio plots for diver separators for flexural. It is noted that the flexure indicates a persistent decreasing pattern with a rise in the time of composite specimen immersion in seawater artificial. A decreasing tendency for the rising fiber-to-
resin ratio of flexural intensity is observed. And the 0°/90° fiber orientation displays optimum flexural power, followed by 30°/60° and 45°/45°.

**Figure 3.** Mean of Signal to noise ratio for Flexural strength

ANOVA for Flexural strength
As seen in Figure 4, residual plots from the ANOVA for flexural intensity are seen. ANOVA is carried out on the basis of a 95% degree of trust.

In Table 2, it is seen that-ratio is highest for fiber orientation with a involvement of 23%, making it the most significant factor followed by fiber to resin ratio and period of immersion in artificial sea water.

**Figure 4.** Residual plots for Flexural strength
Table 2. Analysis of variance for Flexural strength

| Source          | DF | Seq SS  | Adj SS  | Adj MS  | F      | P       | % C |
|-----------------|----|---------|---------|---------|--------|---------|-----|
| Days            | 5  | 678.06  | 678.06  | 135.61  | 2.03   | 0.178   | 32.1|
| F:R ratio       | 2  | 412.92  | 412.92  | 206.46  | 3.09   | 0.101   | 19.5|
| Fibre orientation, deg | 2  | 488.83  | 488.83  | 244.41  | 3.66   | 0.074   | 23.1|
| Error           | 8  | 534.07  | 534.07  | 66.76   |        |         | 25.3|
| Total           | 17 | 2113.88 |         |         |        |         |     |

Interactions plot for the Flexural strength is as shown in the Figure 5. The curves are crossing each other and it indicates a good interaction between the 3 factors, i.e. period of immersion, fibre-to-resin ratio and fibre orientation.

\[\text{Inter-laminar shear strength (ILSS) property}\]

Inter-laminar shear strength is the factor under analysis in this test. This test determines the shear stress bearing capability of the composites between the laminas.

**Taguchi analysis**

Looking at the following mean of means and mean of signal-to-ratio plots, as shown in Figure 5 and Figure 6 respectively, it can be said that maximum strength for composites with least period of exposure, i.e. 15 days and 40:60 fibre to resin ratio with a fibre orientation of 0°/90°.

Figure 6 stand for mean of means p1ots for different factors for ILSS. It is observed that ILSS shows a continuously decreasing trend with increase in the period of immersion of composite specimen in the artificial sea water. Proper trend cannot be concluded for the increasing fibre-to-resin ratio from the above p1ot. The fibre orientation of 0°/90° exhibit highest ILSS followed by 30°/60° and 45°/45°.
Figure 7 shows the different factors for ILSS, reflect mean of means plots. It is found that ILSS displays a steadily declining pattern with a rise in the immersion time of the composite specimen in the seawater artificial. For the increasing fibre-to-resin ratio of the above plot, a proper pattern cannot be inferred. The $0^\circ/90^\circ$ fiber orientation displays the largest ILSS, followed by $30^\circ/60^\circ$ and $45^\circ/45^\circ$.

**Figure 6.** Mean of means for inter laminar shear stress

**Figure 7.** Mean of signal-to-noise ratio for inter laminar shear stress
ANOVA for ILSS
Residual plots from the ANOVA for ILSS are as shown in Fig. ANOVA is performed based on 95% level of confidence.

In Table 3 F-ratio is maximum for fibre orientation with a contribution of 30%, making it the most significant factor followed by time of immersion in sea water and fibre to resin ratio.

Table 3. Analysis of variance for inter laminar shear stress

| Source                      | DF | Seq SS   | Adj SS  | Adj MS   | F    | P      | % C |
|-----------------------------|----|----------|---------|----------|------|--------|-----|
| Days                        | 5  | 44.142   | 44.142  | 8.828    | 3.12 | 0.074  | 38.1|
| F:R ratio                   | 2  | 13.831   | 13.831  | 6.915    | 2.44 | 0.148  | 11.9|
| Fibre orientation, degree   | 2  | 35.360   | 35.360  | 17.680   | 6.25 | 0.023  | 30.5|
| Error                       | 8  | 22.638   | 22.638  | 2.830    |      |        | 19.5|
| Total                       | 17 | 115.972  |         |          |      |        |     |

Interactions plot between different factors is as shown in Figure 9. The curves are crossing each other and it indicates good interaction between the 3 factors, i.e. period of immersion, fibre-to-resin ratio and fibre orientation.

Tensile strength
The ultimate tensile strength (UTS) values from tensile tests are analysed in this section.

Taguchi analysis
As shown in Figure, the following mean of means and mean of signal-to-noise ratio plots show that optimum intensity is shown by composite specimens with a fiber-to-resin ratio of 40:60, a fiber orientation of 0°/90° and 15 days of interaction with sea water.
Figure 9. Interactions plot for inter laminar shear stress

Figure 10. Mean of means for Ultimate tensile strength
The Figure 10 shows average mean graphs for various Ultimate Tensile strength variables. Tensile intensity is found to demonstrate a steadily decreasing pattern with a rise in the time of sample immersion in the sea water. A downward trend from the above plot for the rising fibre-to-resin ratio can be inferred. The 0°/90° fiber orientation displays the strongest UTS, followed by 30°/60° and 45°/45°.
Table 4. Grey-Taguchi analysis

| Expt. No. | Days | F:R ratio | Fibre orientation | Flexural strength | Ultimate tensile strength | Impact strength | Swelling | Weight | Fatigue | Grey relational grade | Rank |
|-----------|------|-----------|-------------------|-------------------|--------------------------|----------------|---------|--------|---------|-----------------------|------|
| 1         | 15   | 40:60     | 0/90              | 1.000             | 1.000                    | 1.000          | 1.000   | 1.000  | 1.000   | 1.000                 | 1    |
| 2         | 15   | 50:50     | 30/60             | 0.449             | 0.427                    | 0.634          | 0.506   | 0.778  | 0.841   | 0.437                 | 5.82 | 4    |
| 3         | 15   | 60:40     | 45/45             | 0.424             | 0.391                    | 0.546          | 0.438   | 0.498  | 0.586   | 0.479                 | 0.480 | 9    |
| 4         | 30   | 40:60     | 0/90              | 0.796             | 0.681                    | 0.807          | 0.585   | 0.906  | 0.806   | 0.406                 | 0.712 | 2    |
| 5         | 30   | 50:50     | 30/60             | 0.436             | 0.390                    | 0.546          | 0.485   | 0.647  | 0.624   | 0.634                 | 0.537 | 5    |
| 6         | 30   | 60:40     | 45/45             | 0.412             | 0.371                    | 0.500          | 0.430   | 0.435  | 0.513   | 0.528                 | 0.456 | 11   |
| 7         | 45   | 60:40     | 0/90              | 0.572             | 0.583                    | 0.807          | 0.547   | 0.794  | 0.667   | 0.533                 | 0.643 | 3    |
| 8         | 45   | 40:60     | 30/60             | 0.433             | 0.389                    | 0.504          | 0.430   | 0.526  | 0.532   | 0.648                 | 0.495 | 8    |
| 9         | 45   | 50:50     | 45/45             | 0.378             | 0.362                    | 0.449          | 0.379   | 0.387  | 0.430   | 0.531                 | 0.416 | 16   |
| 10        | 60   | 50:50     | 0/90              | 0.454             | 0.407                    | 0.592          | 0.518   | 0.703  | 0.630   | 0.347                 | 0.522 | 6    |
| 11        | 60   | 60:40     | 30/60             | 0.423             | 0.386                    | 0.461          | 0.425   | 0.489  | 0.446   | 0.479                 | 0.444 | 12   |
| 12        | 60   | 40:60     | 45/45             | 0.363             | 0.356                    | 0.436          | 0.374   | 0.362  | 0.411   | 0.629                 | 0.419 | 15   |
| 13        | 75   | 40:60     | 30/60             | 0.446             | 0.374                    | 0.577          | 0.438   | 0.550  | 0.586   | 0.506                 | 0.497 | 7    |
| 14        | 75   | 50:50     | 45/45             | 0.400             | 0.362                    | 0.436          | 0.383   | 0.446  | 0.433   | 0.481                 | 0.420 | 14   |
| 15        | 75   | 60:40     | 0/90              | 0.340             | 0.345                    | 0.399          | 0.374   | 0.343  | 0.356   | 0.787                 | 0.421 | 13   |
| 16        | 90   | 40:60     | 45/45             | 0.437             | 0.355                    | 0.550          | 0.428   | 0.515  | 0.492   | 0.508                 | 0.469 | 10   |
| 17        | 90   | 50:50     | 0/90              | 0.392             | 0.344                    | 0.372          | 0.378   | 0.417  | 0.369   | 0.417                 | 0.384 | 17   |
| 18        | 90   | 60:40     | 30/60             | 0.333             | 0.333                    | 0.333          | 0.333   | 0.333  | 0.333   | 0.385                 | 0.341 | 18   |

4. Conclusion
The highest grade of Grey relational rank shows that the results obtained experimentally are closer to idyllic value. In other words, the larger the Grey relational rank, the better will be the multiple performance characteristics. Therefore, experiment 1 in the Table 5 shows the highest Grey relational grading indicating that the parameter of 15 days hygrothermal ageing, 40:60 fibre to resin ratio and 0°/90° fibre orientation in the orthogonal array has the best multi performance characteristics among 18 experiments.

5. References
[1] Basurto F C, García-López D, Villarreal-Bastardo N, Merino J C and Pastor J M 2013 Composites and nanocomposites of ABS: Synergy between glass fibre and nano-sepiolite,
Composites 50 42-47.

[2] Sarawut Rindusit, Parkpoom Lorjia, Kuljira Sujirote and Sunan Tiptipakorn Physical and Mechanical Characteristics of Kevlar Fibre-reinforced PC/ABS Composites 2012 Engineering Journal 16 57-66.

[3] Shao-Yun Fu and Bernd Lauke 1998 Characterization of tensile behaviour of hybrid short glass fibre/calcite particle/ABS composites Composites 29A 575-583.

[4] Jiang L, Lama Y C, Tam K C, Chua T H, Sim G W and Ang L S 2005 Strengthening acrylonitrile-butadiene-styrene (ABS) with nano-sized and micron-sized calcium carbonate Polymer 46 243-252.

[5] Shao-Yun Fu and Bernd Lauke 1998 Fracture resistance of unfilled and calcite particle filled ABS composites reinforced by short glass fibres (SGF) under impact load Composites: Part A 29A 631-641.

[6] Xi-Qiang Liu, Wei Yang, Bang-Hu Xie, Ming-Bo Yang 2012 Influence of multiwall carbon nanotubes on the morphology, melting, crystallization and mechanical properties of polyamide 6/acrylonitrile-butadiene-styrene blends Materials and Design 34 355-362.

[7] Naoya Tsuchikura, Michael C Faudree and Yoshitake Nishi 2013 Charpy Impact value of sandwich structural (CFRP/ABS/CFRP) composites constructed with carbon fibre reinforced epoxy polymer (CFRP) and acrylonitrile butadiene styrene (ABS) sheets separately irradiated by electron beam prior to lamination Materials Transactions 54(3) 371-379.

[8] Chotirat L, Chaochanchaikul K and SombatSompop N 2007 On adhesion mechanisms and interfacial strength in acrylonitrile butadiene styrene/wood sawdust composites International Journal of Adhesion & Adhesives 27 669-678.

[9] Johnny N Martins, Tobias G Klohn, Otavio Bianchi, Rudinei Fiorio and Estevao Freire 2010 Dynamic mechanical, thermal and morphological study of ABS/textile fibre composites Polym Bull 64 497-510.

[10] Bhardwaj Neha, Manjula K S, Srinivasulu B and Shit C. Subhas 2012 Synthesis of exfoliated graphite/ABS composites Open Journal of Organic Polymer Materials 2 74-78.

[11] Jaymin R Desai, Shit S C, Shah M D and Jain S K 2013 Preparation and characterizations of acrylonitrile butadiene styrene (ABS)-cenosphere composites Journal of information, knowledge and research in mechanical engineering 2 (2) 411-416.

[12] Chi-Yuan Huang, Wen-Wei Mo and Ming-Lih Roan 2004 The influence of heat treatment on electroless-nickel coated fibre (ENCF) on the mechanical properties and EMI shielding of ENCF reinforced ABS polymeric composites Surface coating technology 184 123-132.

[13] Mohammed H Al-Saleh, Walaa H. Saadeh and Uttandaraman Sundararaj 2013 EMI shielding effectiveness of carbon based nanostructured polymeric materials: A comparative study Carbon 60 146-156.

[14] Haiyun Ma, Zhongbin Xu, Lifang Tong, Aiguan Gu and Zhengping Fang 2006 Studies of ABS-graft-maleic anhydride/clay nanocomposites: Morphologies, thermal stability and flammability properties Polymer Degradation and Stability 91 2951-5959.

[15] Haiyun Ma, Jun Wang and Zhengping Fang 2012 Cross-linking of a novel reactive polymeric intumescent flame retardant to ABS copolymer and its flame retardancy properties Polymer degradation and stability 97 1596-1605.

[16] Sudeepan J, Kumar K, Barman T K and Sahoo P 2013 Study of friction and wear properties of ABS/Kaolin polymer composites using grey relational Polymer degradation and stability 97 1596-1605.

[17] Pinto R, Afzal A, Souza L D, Ansari Z and Mohammed Samee A D 2017 Computational Fluid Dynamics in Turbomachinery: A Review of State of the Art Arch. Comput. Methods Eng 24(3) 467–479 doi: https://doi.org/10.1007/s11831-016-9165-4.

[18] Afzal A, Ansari Z, Faizabadi A and Ramis M 2017 Parallelization strategies for computational fluid dynamics software: state of the art review Arch. Comput. Methods Eng 24(2) 337–363 doi: https://doi.org/10.1007/s11831-016-9165-4.
[19] Afzal, A., Nawfal, I., Mahbubul, I. M. and Kumbar, S. S. 2019. An overview on the effect of ultrasonication duration on different properties of nanofluids. J. Therm. Anal. Calorim. (135) 393–418 doi: https://doi.org/10.1007/s10973-018-7144-8.

[20] Kumar, R., Sesha, V., Butt, M. M., Ahmed, N., Khan, S. A. and Afzal, A. 2019. Thermo-mechanical analysis and estimation of turbine blade tip clearance of a small gas turbine engine under transient operating conditions. Appl. Therm. Eng. (179) 115700 doi: 10.1016/j.applthermaleng.2020.115700.

[21] Afzal, A., Imran, Mokashi, Khan, S. A. and Muhammad, Azami bin, H. 2020. Optimization and analysis of maximum temperature in a battery pack affected by low to high Prandtl number coolants using response surface methodology and particle swarm optimization algorithm. Numer. Heat Transf. Part A Appl. doi: https://doi.org/10.1080/10407782.2020.1845560.

[22] Mokashi, I., Afghan, S., Nur, A., Abdullah, Hanafi, B., Muhammad Azami, and Afzal, A. 2020. Maximum temperature analysis in a Li-ion battery pack cooled by different fluids. J. Therm. Anal. Calorim. (32) 1–17 doi: 10.1007/s10973-020-10063-9.

[23] Afzal, A., Khan, S. A., Islam, T., Jilte, R. D., Khan, A., and Soudagar, M. E. M. 2020. Investigation and back-propagation modeling of base pressure at sonic and supersonic Mach numbers. Physics of Fluids (32) 096109 doi: 10.1063/5.002015.

[24] Afzal, A. 2020. Response surface analysis , clustering, and random forest regression of pressure in suddenly expanded high-speed aerodynamic flows. Aerosp. Sci. Technol. (107) 106318 doi: 10.1016/j.ast.2020.106318.

[25] R. Pinto, A. Afzal, L. D'Souza, Z. Ansari, and A. D. Mohammed Samee, “Computational Fluid Dynamics in Turbomachinery: A Review of State of the Art,” Arch. Comput. Methods Eng., vol. 24, no. 3, pp. 467–479, 2017, doi: https://doi.org/10.1007/s11831-017-9263-0.

[26] Afzal, Z., Ansari, A., Faizabadi, and M. Ramis, “Parallelization strategies for computational fluid dynamics software: state of the art review,” Arch. Comput. Methods Eng., vol. 24, no. 2, pp. 337–363, 2017, doi: https://doi.org/10.1007/s11831-016-9165-4.

[27] R. Kumar, V., Sesha, M. M., Butt, N. Ahmed, S. A. Khan, and A. Afzal, “Thermo-mechanical analysis and estimation of turbine blade tip clearance of a small gas turbine engine under transient operating conditions,” Appl. Therm. Eng., vol. 179, no. March, p. 115700, 2020, doi: 10.1016/j.applthermaleng.2020.115700.

[28] Afzal, I., Nawfal, I., M. Mahbubul, and S. S. Kumbar, “An overview on the effect of ultrasonication duration on different properties of nanofluids,” J. Therm. Anal. Calorim., vol. 135, pp. 393–418, 2019, doi: https://doi.org/10.1007/s10973-018-7144-8.

[29] N. A. Asif, Afzal, I., Mokashi, S. A. Khan, and H. Muhammad Azami bin, H., “Optimization and analysis of maximum temperature in a battery pack affected by low to high Prandtl number coolants using response surface methodology and particle swarm optimization algorithm,” Numer. Heat Transf. Part A Appl., 2020, doi: https://doi.org/10.1080/10407782.2020.1845560.

[30] Mokashi, S., Afghan, A., Nur, Abdullah, B., Hanafi, Muhammad Azami, and A. Afzal, “Maximum temperature analysis in a Li-ion battery pack cooled by different fluids,” J. Therm. Anal. Calorim., pp. 1–17, 2020, doi: 10.1007/s10973-020-10063-9.

[31] Afzal et al., “Response surface analysis, clustering, and random forest regression of pressure in suddenly expanded high-speed aerodynamic flows,” Aerosp. Sci. Technol., vol. 107, p. 106318, 2020, doi: 10.1016/j.ast.2020.106318.

[32] Afzal, S. A., Khan, T., Islam, R. D., Jilte, A., Khan, A., and M. E. M. Soudagar, “Investigation and back-propagation modeling of base pressure at sonic and supersonic Mach numbers,” Physics of Fluids, vol. 32, no. July, p. 096109, 2020, doi: 10.1063/5.002015.

[33] A. Afzal, I., Nawfal, I., M. Mahbubul, and S. S. Kumbar, “An overview on the effect of ultrasonication duration on different properties of nanofluids,” J. Therm. Anal. Calorim., vol. 135, pp. 393–418, 2019, doi: https://doi.org/10.1007/s10973-018-7144-8.

[34] Asif, A., Khan, S. A., and C. A. Salee, “Role of ultrasonication duration and surfactant on...
characteristics of ZnO and CuO nanofluids,” Mater. Res. Express, vol. 6, no. 11, p. 1150d8, 2019, doi: 10.1088/2053-1591/ab5013.

[35] A. Afzal, M. Samee A. D, A. Javad, A. Shafvan S, A. P V, and A. Kabeer K. M, “Heat transfer analysis of plain and dimpled tubes with different spacings,” Heat Transf. Res., vol. 47, no. 3, pp. 556–568, 2018, doi: http://dx.doi.org/10.1002/htj.21318.

[36] O. David, M. O. Okwu, O. J. Oyejide, E. Taghinezhad, A. Asif, and M. Kaveh, “Optimizing biodiesel production from abundant waste oils through empirical method and grey wolf optimizer,” Fuel, vol. 281, no. May, p. 118701, 2020, doi: 10.1016/j.fuel.2020.118701.

[37] M. Kareemullah, A. Afzal, and K. F. Rehman, “Performance and emission analysis of compression ignition engine using biodiesels from Acid oil, Mahua oil, and Castor oil,” Heat Transf. - Asian Res., no. August, 2019, doi: 10.1002/htj.21642.

[38] A. Afzal, A. D. M. Samee, R. K. A. Razak, and M. K. Ramis, “Steady and Transient State Analyses on Conjugate Laminar Forced Convection Heat Transfer,” Arch. Comput. Methods Eng., vol. 27, pp. 135–170, 2020, doi: https://doi.org/10.1007/s11831-018-09303-x.