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Review Article

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A Review on the Experimental and Numerical Studies of Flow in Liquid Ring Vacuum Pump

Abhishek Kumar and Mohammad Danish[*]

Department of Mechanical Engineering, Bennett University, Greater Noida, India

[*]**Correspondence to:**
Mohammad Danish
Department of Mechanical Engineering,
Bennett University, Greater Noida, India.
E-mail: mohammad.danish@bennett.edu.in

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Abstract

The liquid ring vacuum (LRV) pump has been found to be very effective in evacuating toxic and inflammable gases in petroleum and refinery industries, medical applications, etc. The liquid inside the pump, as it rotates, interacts with the incoming gases which makes the flow behavior complex. The analysis of such multiphase flow behavior inside the pump becomes important to critically analyze the parameters which could affect the pump performance. These parameters are the evacuating pressure, seal liquid, impeller speed, ring shape, etc. Thus, in the past, several experimental and numerical studies have been reported in the literature focusing on the role of LRV parameters on its performance. So, in this paper, a review of these works is presented. Based on this review, it is found that (i) the efficiency of the liquid ring vacuum pump is low and varies for different application depending upon the nature of operation and pump capacity and (ii) the pump performance can be improved by modifying the geometrical design of the pump, operating parameters, and changing the types of operating liquid or varying the concentration of the mixed fluid.

Keywords

Liquid ring vacuum pump, Computational fluid dynamics, Multiphase flow

Introduction

The vacuum pump is a mechanical device, which is used to create vacuum by removing the gaseous molecules from a sealed volume. The first vacuum pump was invented by Otto von Guericke in 1650. Thereupon, with the technological advancement and the industrial needs, several other types of vacuum pump were developed. These include piston [1], screw [2], turbomolecular, rotary vane [3], diaphragm, scroll vacuum pump [4-5] and LRV pump [6]. Among these vacuum pumps, the LRV pump offers certain advantages over the others, like there is no direct surface-to-surface contact, can handle toxic gases, better life span, etc. [6]. Due to these advantages, a preferred application area of LRV pump is the petroleum and refinery industries, where it is used to evacuate the toxic and flammable gaseous mixture [7]. Other application areas of LRV pump are medical application for radiosurgery and radiotherapy, radio pharmacy [8], uranium enrichment [9], and print presses [10].

The construction and working principle of LRV pump is similar to the hydraulic pump as shown in figure 1 with the main components of the pump. An LRV pump typically consists of an eccentrically mounted rotor which rotates inside the pump casing. The pump is maintained with the required level of liquid (generally water) inside the pump casing, when impeller rotates, the liquid inside each blade cell is forced to rotate along the impeller.

Due to the centrifugal action, the incompressible liquid between the impeller blade and pump casing forms a liquid-ring shape as shown in figure 2. The shape

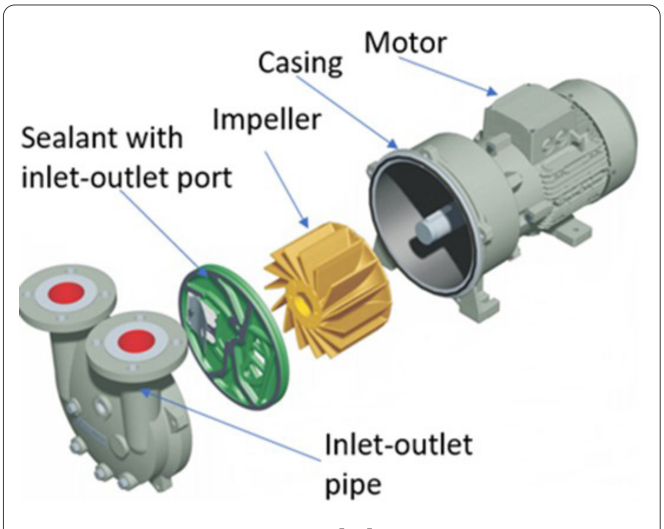

Figure 1: Major parts of LRV pump [11].

of the liquid ring causes a gradual increase and decrease of volume as the blade passes from top dead center to bottom dead center. When the volume starts increasing, a low-pressure between the liquid ring and hub develops which opens the inlet port. The opening of the inlet port causes the suction of the gaseous molecules into the vacuum pump (from cell 1 to cell 5 in figure 2). Similarly, when the blades move from bottom dead center to top dead center the sucked gases get compressed. Once the gases are compressed to atmospheric pressure, the exhaust port opens, and the compressed gases leave the pump (from cell 7 to 11 in figure 2).

The liquid circulating inside the LRV pump interacts with air/gases and experiences chaotic change in pressure and velocity. This complex behavior of fluid inside the pump greatly affects its performance. Therefore, to understand the physics of multi-phase flow at different geometric and operating conditions, several experimental and numerical research was conducted by the researchers. In this review paper, our aim is to present a compiled review of these works which can guide prospective researchers in this field.

This review paper is structured as follows. In the Design Optimization section, literature on recent developments to improve the performance of the LRV pump is presented. In the next section, the development of LRV pump based on the operational optimization is provided. Finally, the paper concludes with the guidelines for future research direction and a summary of the paper.

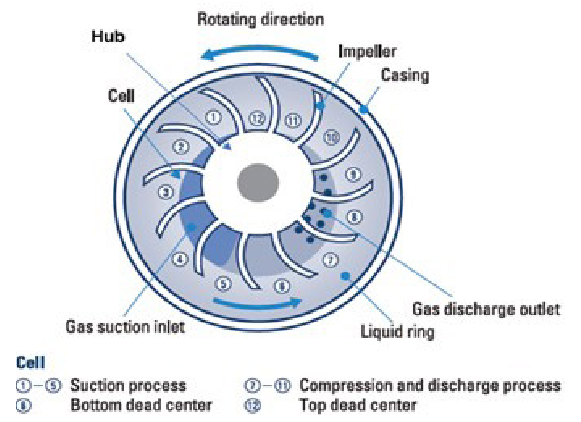

Figure 2: Operating principle of LRV pump [12].

Design Optimization

The understanding of physics behind the pumping operation is important for optimizing the pump design. In the pumping operation the evacuating gaseous molecules compressed with the circulating liquid or seal liquid. The gaseous molecules interact with the seal liquid from ingestion to exhaust and part of the seal liquid also goes out with the gas molecules which is compensated back to the pump. The experimental and analytical analysis of these fluid flow interaction problems become very challenging, especially for the complex geometry with turbulent flow. Therefore, computational methods such as Computational Fluid Dynamics (CFD) become ideal for obtaining the approximate solution for such fluid domain problems. The CFD provides computer-based solutions by solving the governing equations derived from the laws of fundamental mechanics. The governing equation is the conservation of mass and momentum coupled with energy equation which are solved for variety of fluid domain problems.

To investigate the multiphase fluid interaction inside the pump, Kakuda et al. [13] simulated the liquid-air flow in a LRV pump using the Moving Particle Semi-implicit (MPS) method. The MPS method is used for solving the incompressible, multiphase flow simulation applied to fluid-structure interaction problems. The simulated results from the MPS scheme for the liquid-air interaction were compared with Petrov-Galerkin method as well as the experimental results and a good agreement was observed. Ding et al. [14] simulated the multi-phase flow of liquid ring vacuum pump using the volume of fluid model. The volume of fluid method is a powerful method of solving the interface-interaction problems of CFD. This model is based on Eulerian approach, achieved by solving the transport equation for volume of fraction given as [14].

$$\frac{\partial}{\partial t}\int_{\Omega(t)} \rho i F_i d\Omega + \int_{\sigma} \rho_i \left(v - v_{\sigma}\right) * n F_i d\sigma = 0 \qquad (1)$$

Where, $\Omega(t)$ is the computational volume domain, σ is the surface of the control volume $\Omega(t)$, ρ_i is the local fluid density of ith component, F_i is the fractional volume of the ith fluid component, v is the surface velocity, v_σ is the surface motion velocity, and n is the normal of surface (σ) towards outward.

Using (1), Ding et al. [14] performed three-dimensional transient CFD simulation on 2BE203 series LRV pump and compared the results with experimental results.

The liquid-gas interface, viscosity of the operating fluid and the cavitation phenomenon of multiphase flow at various locations inside the LRV pump causes noise and vibration. The excess of these vibrations may cause the mechanical fault of the rotating components leading to failure of the pump. Zhang and Guo [15] conducted an experimental study on

LRV pump to analyze the liquid-gas transient behavior and hydraulic excitation between the casing and impeller blade through vibration analysis. The Strouhal number was used to establish the relationship between the frequency of the pump casing and the frequency of the flow characteristic as [15].

$$St = \frac{\pi D}{Z}\frac{f}{u} = \frac{f}{f_{bpf}} \quad (2)$$

Where, Z is the number of blades, *f* is the vibrational frequency, *D* is the diameter of the impeller, f_{bpf} blade passing frequency, and *u* is the velocity at the impeller-tip. The root-mean-square value was used to represent the vibrational magnitude for the diagnosis of fault in the LRV pump system, given as [15].

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} \quad (3)$$

Where, *n* is total number of sample and x_i represents the instantaneous vibration.

Cavitation is an important phenomenon especially in the application that operates on low to high pressure range. Ding et al. [16] predicted the cavitation effects on the performance of pumps for industrial applications. In the liquid ring pump, low suction pressure is limited due to the vapor pressure of the operating liquid. As below 33 mbar of suction pressure, water begins to boil, and it will not give the desired pressure [17]. Therefore, suction pressure must be higher than the vapor pressure by considerable value to avoid cavitation. Radle and Shome [18] has numerically predicted the cavitation in LRV pump used in Aircraft fuel system using the Multiple Reference Frame and Transient Sliding Mesh methodology in CFD analysis. The multi-phase fluid mixture consisting of liquid Jet-A fuel ($C_{12}H_{23}$), vapor phase of Jet-A fuel and dry air is used in numerical analysis. The numerical result shows the prediction of cavitation more accurate with Transient Sliding Mesh methodology than the Multiple Reference Frame methodology. However, it should be noted that these results were not validated with the experimental data.

The provision of clearance between the rotary and stationary components is the necessity of the mechanical system. Researchers have studied the causes and effects of leakage of fluid in pumps and compressors. Prager [19] mathematically investigated the various losses of power in the pump and calculated the power required during the pumping operation. It was observed that the hydraulic loss, volumetric and thermodynamic loss, and mechanical loss were 50%, 14%, and 3%, respectively. The major portion of hydraulic loss was identified due to fluid friction at the wall and at the impeller blade, the losses due to fluid flow are delivery loss and internal leakage. However, these analytical results need to be validated with experiment. Wu et al. [20] explained the leakage phenomenon in water jet pump using Stereoscopic type of the Particle Image Velocimetry method to show the effect of tip leakage flow. The turbulence was observed as non-homogeneous in the region of Tip-Leakage Vortex. Zhang et al. [21] installed high speed camera to analyze the leakage and cavitation at the tip of the blade in axial flow pump. Further Zhang et al. [22] investigated the effect of axial clearance of multiphase flow in liquid ring vacuum pump. The grid independency test result for the hexahedral mesh of 2BEA-203 LRV pump suggested total number of cells to be 5164000 for maintaining the balance between the computational cost and accuracy. The simulation result with the RNG k-ε model is more accurate than the standard k-ε model. It was observed that the pressure difference between the adjacent cell of the impeller causes the back flow of the gas-liquid flow which is more predominant at the suction region in the LRV pump. It was also noticed that the leakage flow penetrates the impeller blade towards the suction side. The back flow of these fluids reduces the suction capacity hence reducing the performance of the pump. The efficiency of the vacuum pump is calculated as [22].

$$\eta = \frac{p_1 * Q * ln\left(p_1/p_2\right)}{P} \quad (4)$$

Where, p_1, p_2 are the pressure at suction and exhaust side, respectively, Q is the gas flow rate and *P* is the shaft power.

The blade encounters variable pressure throughout blade surface and their design plays an important role in the performance of the vacuum pump. Wei et al. [23] numerically simulated the winglet-composite blade tip and analyzed their effect on leakage through tip clearance. The numerical result shows that the reduction in pressure difference between the pressure and suction side of the blade due to the winglet tip causes the flow extension and the reduction in leakage. Therefore, the winglet tip can provide better vacuum capacity and higher efficiency. Liu et al. [24] investigated the effect of tip clearance sizes on the performance of hydraulic pumps. The RNG k-ε turbulence model is used for the solution in the CFX software. Convergence is achieved under the residuals value of 10^{-5}. It was observed that the leakage vortex intensifies with increase in tip clearance, also the pump head reduces which causes decrease in pump performance. Zhang et al. [21] conducted the experiment on 2BEA-203 LRV pump to study the effect of axial clearance for multi-phase flow in the pump. They observed that the leakage at the tip of blade is mainly caused due to the forward-curved shape of the blade.

Operational Optimization

The impeller transfers required driving force to liquid to form the desired shape of liquid ring. The liquid ring plays a major role in determining the intended compression and suction pressure inside the LRV pump [25]. Hence the rotational speed must be determined for efficient operation of the pump. Raizman et al. [26] conducted an experiment on VVN-3 LRV pump to measure the instantaneous velocity of the liquid ring inside the pump using a comb-like probe. The calculated pressure and velocity at each radial section shows that the velocity profile of liquid ring varies in both the radial and circumferential direction while the pressure profile varies only in in the radial direction. Powle et al. [27] investigated the variation in pumping speed and their effect on the performance of the

LRV pump. It was observed that the volumetric efficiency or the pumping speed increases with increase in flow rate and increase in temperature of the seal liquid and vice versa. It was also found that the performance of the vacuum pump depends upon the various combination of geometrical and operating parameters.

Prager [19] developed a mathematical relation to calculate the efficiency of the pump. In Prager's model the frictional loss by the liquid inside the pump was calculated as [19].

$$N_l = 0.708\frac{\rho}{2}\omega^3 r_2^5 \mathrm{Re}^{-0.1732} \tag{5}$$

Where, N_l is the frictional loss by the fluid, ρ is the density of the water, is the angular velocity of the impeller, r is the impeller radius, and Re is the Reynolds number.

Since Prager [19] did not consider the effect of the axial width of the impeller, so Huang et al. [28] improved the Prager's model by including the axial width (b) of the impeller in the calculation of energy loss due to fluid friction:

$$N_l = 0.708\frac{\rho}{2}\omega^3 r_2^5 \mathrm{Re}^{-0.1732}\left(1+f\frac{b}{r_2}\right) \tag{6}$$

The mathematical model (6) was analyzed on three different medium capacities of single stage vacuum pumps (2BE1103, 2BE1253, and 2BE1353). Following Huang et al. [28] model the shaft power (N) is calculated by the expression:

$$N = N_g + N_l \tag{7}$$

$$N_g = \frac{k}{(k-1)} p_s q_{th}\left[\left(\frac{p_d}{p_s}\right)^{\frac{k-n}{(k)}} - 1\right] \tag{8}$$

Where, N_g is the power required for the adiabatic compression of the gas, q_{th} is the volumetric capacity of gas, k, n are the gas expansion index and p_d, p_s are the discharge and suction pressure, respectively.

A comparison of shaft power, as predicted by the model (7) and (8) at different inlet pressure and rotational speed is shown in figure 3. The model results were also compared with the experimental results. Clearly, the model is able to capture the variation of shaft power with respect to inlet pressure and rotational speed. These results were also found to be in good agreement with the experimental result data.

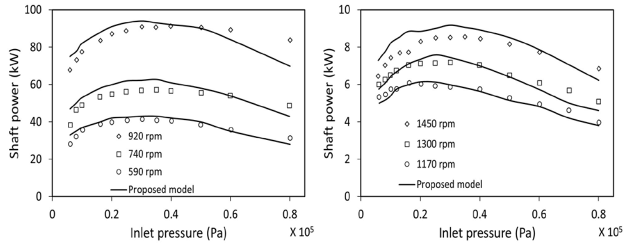

Figure 3: Comparisons of *N-Ps* of two LRVP 2BE1103 (left) and 2BE1253 (right) (adapted from Huang et al. [28]).

Pandey et al. [25] performed an extensive numerical and experimental study on the LRV pump. Their CFD simulation results show that the liquid ring center shifted slightly towards the suction port when running at lower speed, and at higher operation speed the ring center shifts towards away from the suction port. In the simulation they used three different sizes of grids, 1.26 million, 3.42 million and 6.7 million cells, and grid independency was obtained for 3.42 million cells. The numerical and experimental results, it was observed that the shape of the liquid ring depends only on the centrifugal force, however it greatly influences the ingestion, compression, and discharges of the fluid. Pandey and Shih [29] analyzed multiphase flow in LRV pump using CFD simulation and developed physics based Reduced-Order Model. In this model, the author has established mathematical relation between the geometrical configuration and operating parameter using CFD simulation for the LRV pump. The base curve reflects the geometric affects and the operational parameters reflected by the correction to the base curve. The correction factor is determined from the CFD simulation. The base curve is selected as circle as given in equation (9). The Reduced-Order Model can be used to predict the liquid ring shape, the rate of air through suction and the required shaft power for the pumping operation. Equation (10) can be used to determine the shape of the liquid ring which is the function of the geometric and operating parameters.

$$\left(x - x_{cb}\right)^2 + \left(y - y_{cb}\right)^2 = r_1^2 \tag{9}$$

$$r_2 = r_1\varphi \tag{10}$$

Where, φ is the correction factor, r_2 is the radial distance from the base curve, r_1 is the mean of the blade tip and hub radius, x_{cb} and y_{cb} are the coordinates for the base curve.

The operating liquid circulating inside the LRV pump experiences chaotic changes in the pressure-velocity profile and enormous frictional losses. The properties which hinder the performance of pumps are turbulent drag reduction coefficient, viscosity, vapor pressure, density, etc. [30]. The vacuum pump performance can be improved by selecting the suitable operating liquid or by using water-soluble additives that reduce the turbulent drag reduction coefficient. Zhang et al. [31] used Xanthan gum (XG) as an operating liquid based on turbulent drag reduction theory for improving the energy-efficiency of the LRV pump. The Herschel-Bulkley model gives the excellent fitting relationships between the shear-thinning and the dynamic yield stress as [31].

$$\sigma = \sigma_0 + k\gamma^n \tag{11}$$

Where, σ is the shear stress, σ_0 is the dynamic yield stress, k is the consistency index, γ is the shear rate, and n is the power low index.

The consistency index increases and decrease of the power law exponent with the increase of XG concentration represents the increase in solution viscosity which disobeys the Newtonian fluid behavior. Figure 4 (left) represents the relationship between shaft power and inlet pressure as a function of XG concentration in water at 25 °C inlet temperature. Figure 4

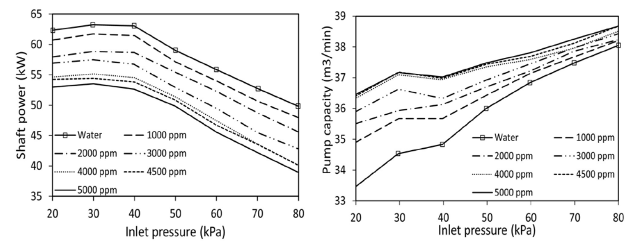

Figure 4: Comparison between shaft power and inlet pressure (left) and pump capacity and inlet pressure (right) (adapted from Zhang et al. [31]).

(right) shows as the pump capacity increases the inlet pressure decreases considerably at 25 °C inlet temperature. Figure 5 shows the efficiency of the pump as the function of suction vacuum pressure and XG concentration in the water. It can be observed that the LRV pump efficiency increases with an increase in XG concentration in the operating liquid.

Zhang et al. [32] investigated the heat transfer behavior of polymer solutions in the LRV pump. The aqueous solutions of flexible Polyacrylamide (PAM) and rigid XG reduce the frictional flow and increases the flow rate in the heat exchanger used in LRV pump system. The study shows that these polymetric solutions can save 1.5% to 17.5% energy consumptions in LRV pump. The comparison of Heat Transfer Rate and Energy Saving Rate for different polymer solutions (XG and PAM) at different concentration levels at velocity v = 0.76 m/s has been shown in figure 6.

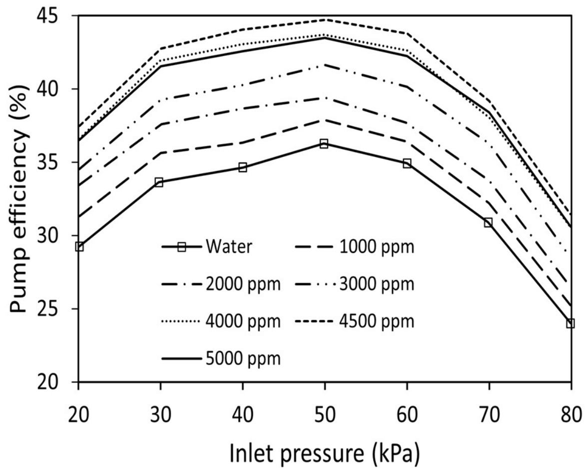

Figure 5: Comparison between Pump efficiency and Inlet vacuum pressure as the function of XG concentration (adapted from Zhang et al. [31]).

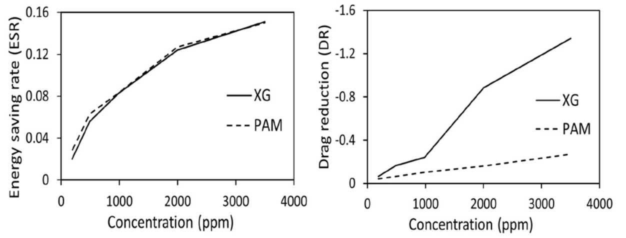

Figure 6: Comparison of ESR (left) and DR (right) for XG and PAM concentration (adapted from Zhang et. al. [32]).

The LRV pump is used for low vacuum range application due to high vapor pressure of water (23.4 mbar at 293 K). The seal liquid such as mercury having high density with low vapor pressure (0.00163 mbar at 293 K) can be used to produce low vacuum in LRV pump. Giegerich et al. [33] conducted a series of experiments using mercury as operating liquid in the LRV pump. From the experiments it was observed that mercury as operating fluid can be a viable solution for achieving low vacuum in the pump. However, the mercury has low flowability hence the piping system must be modified, and special heat-exchanger is required due to low heat transfer coefficient of mercury. Also, due to the high toxicity of mercury the waste handling is very challenging.

Future Direction of Research

Based on the review presented in this paper, it can be concluded that even though LRV pump has extensive application, yet limited research has been conducted to investigate the multiphase flow analysis in LRV pump. Multiphase flow analysis is important in understanding the physics of the operation and helps in optimum designing of pumps for efficient operation. Hence, there are a few areas which need to be discovered and require extension of the current research work. These are as follows:

- Since the gas inside the pump undergoes severe pressure change from suction to discharge port, so under this situation the temperature cannot be treated as constant. Also, the high temperature of the gases may cause the phase change of seal liquid which in turn, can affect the performance of the LRV pump. Therefore, numerical analysis considering energy equations can provide better insights.
- Machine learning based solutions for performance monitoring and fault diagnosis can be explored.
- The numerical solution of LRV pump can help in selecting optimum geometry such as blade angle, rotational speed, clearances, and size of the pump etc. for designing the efficient pump.
- Different CFD models can analyze the chances of bubble formation due to the low ingestion pressure and suggest desired operating conditions to avoid the pump from cavitation.
- The pump performance can be improved further using the alternative of water or the mixture of novel fluid like XG and PAM with optimum concentration as operating liquid that can be numerically estimated with CFD simulations.

Conclusion

This paper reviews the work into the recent development, performance challenges, and design optimization of multiphase flow in LRV pump. The following conclusion can be inferred from the above literature survey.

- Since the LRV pump does not have direct contact of impeller with casing and uses water as seal liquid, the pump can handle very smoothly chemically reactive, mixture of gases with impurity and flammable gases.
- Presently the world is concerned about the energy crisis therefore several research has been conducted in the last decade to make the pump more energy efficient.
- Several CFD models have been proposed to analyze the multi-phase flow and successfully improved the performance of the pump through optimum geometrical design of the pump.
- The numerical solution has been found very effective in analyzing the pump and provides optimum operating condition for improved pump performance.
- To make the pump more efficient researchers also used different fluids for the seal liquid other than water.

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Conflict of Interest

The authors declare no conflict interests that are relevant to the content of this article.

Credit Author Statement

Abhishek Kumar: Conceptualization, Methodology, Resources, Investigation, Formal analysis, Writing - original draft preparation; Mohammad Danish: Conceptualization, Methodology, Writing - review and editing, Supervision. All the authors read and approved the manuscript.

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