Influence of inlet pressure and geometric variations on the applicability of Eductor in low temperature thermal desalinations

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Article history:
Received 8 September 2020
Accepted 30 March 2021
Available online xxxx

Abstract
This paper explores the potential of water jet eductor to replace large condensers and vacuum pump in the thermal desalination systems, with heat source temperatures below 95 °C. The operational limit of eductor has been investigated for active vapor transport and condensation to produce permeate. Combined system and its operational principle have been proposed with critical examination based on suction performance of Eductor. Experimental and computational study are the primary methodology of this work. The computational analysis of single-phase flow in Eductor, is in proper agreement with the experimental data. The result showed primary pressure & area ratio has positive impact and swirl ratio has negative impact on suction. The extended thermal analysis summarizes strength of Eductor while working with lower temperature sources and optimum cooling capacity of proposed system. Considering the simplicity and reduction in footprint, proposed application has been highlighted. The research disseminates knowledge on maximum vacuum generation capacity of Eductor and operational limit of thermal desalination system.

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1. Introduction

Global water stress due to unavailability, overconsumption &/deterioration, has been a major concern. Although 71% of earth’s surface is covered with water, 96.5% of them are salty, hence processing is essential prior to utilization. Desalination being one of the proven alternatives, research and development on optimization for economical water production has been a priority, with adaptation of alternative renewable & sustainable energy sources and process simplifications. To ensure water availability two prospects are essential; production control and or consumption control. (Ajbar & Ali, 2015) (Chowdhury & Al-Zahrani, 2015) This work is focused towards developing medium scale, simple water desalination unit. The prime objective of this research is to examine the thermal performance and applicability of water jet Eductor as a combined vacuum generator and condenser. This study is focused on operational capability and controls associated with Eductor (Alfa Laval, 2019) (Population Pyramid, 2019) (Centers for Disease Control and Prevention, 2016).

Publications on geometrical perspective and influence on the performance of water jet Eductors are limited. Primary nozzle geometry, position and corresponding influence on performance (critical back pressure, entrainment ratio, pressure distribution, etc) were studied by Ariafar & Toorani (2012), Behtash et al. (2011), Sharifi & Sharifi (2013), Seckin (2018), Xu et al. for application in the refrigerant system and air-jet ejector. Banu et al. (2016) studied enhanced mixing capacity of Eductor, with inlet swirl flow. Effect of throat length and diameter have been studied by Saini et al. (2018a), Saini et al. (2018b) and Wang et al. (2011), and found that suction pressure increases with increasing throat length and throat diameter has less significant effect. Macia et al. (2019a), Macia et al. (2019b), studied the vacuum generation capacity of the ejectors, by using experimentally verified computational model. Anwar et al. (2019) made a bibliometric analysis to emphasize the importance of jet suction technology for abrasive jet machining. In contrast to existing literature, this research work aims in utilizing vacuum pumping, two-phase mixing, and condensation, all operational capabilities of Eductor in the process. In addition, most of the literatures related with ejector (eductors and ejectors are most of the time interchangeably used and have
similar construction but different functionalities, here water jet systems are referred as eductor while all other fluid jet system are referred to as ejectors) prioritizes on air jet or steam jet systems, while this work focuses on application of water jet Eductor for freshwater production. Critical examination of impact of Eductor performance on water desalination process is prime outcome of this work. Eductor performance has been measured in terms of its suction capacity with variation in flow (primary pressure & swirl intensity (Swirl Ratio)) and geometry (primary nozzle opening & area ratio). The maximum suction pressure is correlated with corresponding saturation pressure of the water and required temperature source for vapor generation. Additionally, the maximum cooling capacity of Eductor is identified to limit the operation and optimization target.

2. Application of eductors in low temperature thermal desalination: a case of vacuum membrane distillation

2.1. Rationale

Availability of water, limited freshwater at natural state, increasing demand and production of potable water are major water concerns. The sources such as waste, brackish and seawater have become priority compared to traditional one, to ease the availability (Pangarkar et al., 2014). The study of the freshwater production process, from alternative sources has become very important. Desalination (thermal, pressure and / chemical activation) being a popular method in production of freshwater (Youssef et al., 2014), R&D has prioritized process optimization for economical and quality water production. The hybridization of thermal and pressure activation processes led to development of Membrane Distillation (MD), which overcomes limitations like system size, concentration polarization, etc., with its capability of processing high saline water from low-grade heat source (Deshmukh et al., 2018). A more focused picture with possibility of utilization of Industrial Waste Heat or Renewable Energy sources has developed increasing interest in this technology; as this can be a sustainable water production process (Alkaisi, et al., 2017; Pangarkar, et al., 2016).

Fig. 1 is the schematic diagram of Vacuum Membrane distillation (VMD), which has become one of the preferred MD technologies. Comparatively low convective heat loss and lower mass transfer resistance can be achieved by applying low pressure (equilibrium to vapor pressure) at downstream (permeate side) in VMD, hence higher flux and thermal efficiency can be achieved (Banat & Simandl, 1995)(Urutaga et al., 2001)(Koo et al., 2013). Despite the fact of better performance of VMD, the use of vacuum pump and a separate condenser unit makes it a complicated and bulk unit together with higher production costs (Hung et al., 2017).

Eductors operates with the conversion of pressure energy in motive fluid (water) to velocity energy, which creates a low-pressure zone for suction of secondary fluid (water vapor), as shown in Fig. 2 (Oh & Ngoc, 2015). The condensing and vacuum generation capacity with eductors were studied earlier. Zhang et al. (2012) performed experimental study of water jet eductor for suction of secondary steam. The complete condensation through Direct Contact Condensation (DCC) was reported. Similarly, Saini et al. (2018a), Saini et al. (2018b) and Macia et al. (2019a), Macia et al. (2019b) explains the usability of eductor in vacuum generation. The value of condensing capacity is dependent on primary mass flow rate while the value of suction capacity is dependent on primary and outlet pressures. The suitable limit of operation based on the feed water temperature allows a single system to fulfil both the requirements. The concept on introduction of Eductor in VMD can overcome limitations in certain isolated freshwater production systems, by replacing vacuum pump and condenser unit. In addition to complexity, significant footprint reduction can be achieved. Fig. 2 is the VMD system with Eductor for combined vacuum generation and condensation. Vacuum pressure is the prime influencing factor in VMD, hence identification of factors influencing it is essential (Banat et al., 2003). Scale formation on moving parts is another important challenge in almost all
desalination process, since eductor lacks moving parts, the impact is minimum with it (Alahmad, 2004).

2.2. Energy scenario

Current effort and time in Research and Development of Water Desalination system focuses on system size and energy efficiency. This part theoretically discusses the energy scenario in VMD & Eductor.

In a typical VMD system, thermal and electrical energy are used. The major processes are feed heating (E1), feed circulation (E2), Vacuum pumping (E3) and permeate condensation & sensible cooling (E4). E1 and E4 is thermal energy and E2 and E3 are electrical energy. In presence of Eductor, energy required for feed heating and circulation remains same, while energy supplied to Eductor will be utilized for Vacuum generation, condensation, and sensible cooling. Hence, calculation of E3 and E4 will provide a contrasting factor. Vacuum pump in VMD evacuates non-condensable gas from permeate chamber and maintains vacuum pressure. Applying adiabatic vapor expansion and contraction at steady state, energy required for vacuum pump is given by Eq. (1); (Xie et al., 2016)

\[ E_3 = \frac{m_{nc}RT_p}{MW} \left[ \frac{P_{out}}{P_p} \right]^\phi - 1 \]  

where \( m_{nc} \) is mass flow rate of non-condensable gas, \( \phi_{p2} \) is vacuum pump efficiency, \( R \) is Universal Gas Constant, \( T_p \) is permeate side temperature, \( MW \) is molecular weight of air, \( P_{out} \) is the vacuum pump exit pressure, \( P_p \) is vacuum pump inlet pressure and \( \phi \) is adiabatic expansion coefficient which is a fraction of heat capacity at constant pressure to constant volume.

Thermodynamically, for conversion of vapor to usable water, de-superheating from permeate inlet temperature \( T_{pi} \) to condensation temperature \( T_{pc} \) and then subcooling to outlet temperature \( T_{po} \) is essential. Hence, total energy required for the process is energy involved in each (Eq. (2));

\[ E_4 = m_p \int_{T_{pi}}^{T_{po}} C_p dT + m_p \int_{T_{po}}^{T_{po}} C_p dT \]  

where \( m_p \) is mass flow of permeate, \( C_{p,g} \) & \( C_{p,l} \) are heat capacities of water vapor and liquid respectively.

Usually, required cooling energy is processed using condenser. Considering a common copper coil type condenser with tube diameter 15 mm, coil diameter 200 mm with 10 turns enclosed in cylindrical water tube of diameter 230 mm and length 320 mm. Mass flow rate required to achieve \( E_4 \) in a coil heat exchanger maintaining temperature difference \( \Delta T \), with water vapor flowing in the coil and water as cooling fluid is given by Eq. (3); (Incropera et al., 2007) (Bonafoni & Capata, 2015)

\[ Q_c \equiv \frac{\Delta T}{R_1 + R_2 + R_3} \]  

where the value of \( Q_c \) (cooling capacity) should be equal to \( E_4 \) to achieve the outlet requirement for fresh water, \( R_1, R_2 \) & \( R_3 \) are heat transfer resistance due to water vapor, copper wall and water.

In an Eductor, at low pressure zone of primary fluid passage, secondary fluid entrains, and subsequently direct contact heat and mass transfer occurs. During the process, it first ejects non-condensable gas from permeate chamber and then pulls vapor in the water stream. Applying Bernoulli’s equation between primary flow inlet and nozzle (velocity at inlet is negligible compared to nozzle outlet) suction pressure and mass flow rate at available inlet pressure is given by Eqs. (4) and (5);

\[ \frac{P_{li}}{\rho} = \frac{P_{sc}}{\rho} + \frac{V_{mz}^2}{2} \]  
\[ m_{in} = \rho A_{en} V_{mz} \]  

Energy balance in secondary nozzle considering, adiabatic reversible flow, entrained mass flow is (Eq. (6));

\[ m_e = \rho A_{en} \sqrt{2(h_{pi} - h_{sc})} \]  

where, \( h_{pi} \) in the enthalpy at inlet pressure of vapor and \( h_{sc} \) is enthalpy at suction chamber pressure given by equation.

Energy required by Eductor for suction and heat & mass transfer is the pumping power (Eq. (7)).

\[ P_{ed} = \frac{gm_e H_{li}}{\epsilon_{ep}} \]
In DCC, for an adiabatic system, energy loss (vapor) \(\equiv\) energy gain (liquid). To achieve \(E_4\) amount of energy transfer for complete condensation inside Eductor, considering temperature difference like the conventional heat exchanger required mass flow rate can be calculated as (Eq. (8));

\[
E_4 = \frac{Q_c}{Q_{ed}} = \frac{\dot{m}C_p(T_2 - T_1)}{	ext{Initial & final temperatures of primary fluid}}
\]

The Section 2.1 describes the role of eductor in membrane distillation and Section 2.2 describes the cooling mechanism within the eductor system. The thermal energy management is a major area on this kind of processes. Eq. (8) explains the relationship for flow rate requirement by eductor to achieve required amount of cooling. Eductor has potential of replacing vacuum pump and conventional heat exchanger system in a low temperature thermal desalination process, such as VMD, MED and MSF. Medium scale systems are preferred in geographically isolated regions, where technical simplicity is essential for low investment & maintenance cost along with feasibility of localized manufacturing & maintainability. Centralized manufacturing and distribution are not the kind of format that can reach to global corners, instead resource development by the community for the community is required. The activity aims in developing a simple & compact system for freshwater production.

3. Methodology

The identified operational and geometric parameters were examined based on their ability to generate vacuum in the system. A computational method was experimentally verified and implemented for study of operational conditions and geometric variations. Computational and experimental methods have been explained below.

3.1. Experimental method

Fig. 3 and Fig. 4 are experimental setup and its Piping and Instrumentation Diagram (P&ID) diagram, used for experimental purpose. The test setup was developed aiming to cover all aspects of the experiments during the performance study of Eductor. For maximum suction pressure measurement, suction valve (V308-02) was turned off (turned on for suction flow measurement) and measurements at various operating conditions were noted. The outlet valve (VV308-03) was fully opened to atmospheric pressure and loop control valve (V308-06) was closed to ensure complete open-loop flow. The loop uses double stage centrifugal pump with pressure tank (PT308-01) for consistent operation (Pressure & flow). Flow condition variation were adopted with inlet and outlet valves (VV308-01 & VV308-03). Pressure transducers were installed at inlet and suction for primary (range 1–5 Bar) and secondary (range -1–0 Bar) pressure measurement and vortex flow meter was installed at inlet to monitor the flow rate.

Experimental uncertainty and repeatability of each of the parameters were calculated to ensure reliability of generated data. The measured suction pressure is the maximum attainable suction for the operating condition. The Eductor considered for this study is the commercial product, assumed to be a reference design case for further study in the framework.

3.2. Computational method

Computational analysis was performed in commercial CFD software ANSYS CFX, using computational facility of RMIT University, Melbourne, Australia. The geometry used for this study is prepared by reverse engineering the available commercial product.

3.2.1. Computational domain

Fig. 5 is the geometric detail. The simplified computational domain was prepared in Catia V5. The location of suction position has been modified such that total suction surface area remains constant. The modification allows simpler meshing and better convergence (Shah, et al., 2014) during the calculation.

3.2.2. Boundary conditions

Fig. 5 shows the major boundaries. Pressure of 20, 40, 60, 80, 100, 120, 140 & 160 kPa at inlet and atmospheric pressure at the outlet were defined as two major boundary conditions, walls were treated as no slip. Since the study focuses on the identification of maximum suction capacity of Eductor, suction opening is defined to be a wall, which resembles fully closed suction valve (analogous to the experiment). Single species flow with water as the motive fluid was defined and resultant suction pressure was monitored. Turbulence modelling of the flow was done with k-\(\varepsilon\) turbulence model.
model since it had better convergence and agreement with the experimental results (Shah et al., 2014).

3.2.3. Grid independent test

Computational sensitivity and reliability are dependent on the mesh size. This study examines convergence of 4 parameters, velocity at three points, and suction pressure. Block aided, structured mesh developed in ICEM (Integrated Computer Engineering and Manufacturing), of size 0.35 Million were used for this study (Fig. 6). Fig. 7 is the Mesh Independent Test (MIT) plot for velocities and suction pressure, the primary and secondary horizontal axis are independent. Mesh interval of 1.5 times was selected and computation in each of the intervals were performed to attain 1% convergence to ensure solution reliability.

4. Results & discussion

4.1. Verification of computational model

Experimental studies were performed with the setup shown in Fig. 3. Primarily, the evaluation of suction at different inlet pressures were examined together with the computational method to
further explore it. Fig. 8 is the comparative plot for suction pressure with respect to different inlet pressures, observed computationally and experimentally. The random uncertainties of measured experimental data were in the range of 0.07% to 0.5%. A linear relation between maximum suction pressure and inlet pressure were observed, computational and experimental results were found to have a maximum deviation of around 15.3%. At low-pressure conditions, better acceptance was observed, increasing leakages in the cases with higher inlet pressure, may have caused increasing variation.

The section beyond this adopts the verified computational model to further explore the flow phenomenon inside the Eductor.

4.2. Effect of nozzle opening factor

It is customary and mandatory for manufacturers to quote, best operating point and respective efficiency of the system, but the consistent operation of a fluid system at a single specified point is rare. Deviating from BEP results in lower performance/deviation.
One of the accepted theories for pressure & velocity regulation to maintain consistent operation is balancing Bernoulli’s theorem with the spear valve by controlling the percentage opening of nozzle. Fig. 8(a) is nozzle-spear valve assembly, where the linear movement of spear valve from $x$ to $x'$ against a fixed position $A$ regulates opening percentage of the nozzle, this overcomes the variations and deviations.

Fig. 8(b) is the surface plot for suction pressure at varying inlet conditions, for different nozzle opening. It explains the possibility of acquiring the same suction pressure at different combinational inlet pressure and nozzle opening. If the output requirement is 80 kPa, this can be achieved with inlet pressure ranging from 160 kPa to 280 kPa at different spear valve position. The output rigidity and its dependency on input parameters can be flexible, with an additional feedback control system. On the other hand, best performance can be maintained. Either of the prospects strengthens the reliability of the system. In the prospective application of MD, it is essential to maintain pressure difference for vapor transfer through a hydrophobic membrane. Implementation of spear valve nozzle assembly can overcome operational variation in the system, by using feedback-based spear valve position adjustment.

Fig. 9 is the feed temperature at different inlet pressure for respective calculated suction pressure. The corresponding saturation temperature suggests, with lower amount of suction pressure and higher nozzle opening factor, lower temperature feed source can be utilized. Temperature sources from 58 °C could be utilized in such kind of Eductor assisted system. In some of the industrial waste heat-based membrane distillation process, operational limitation due to one of the functionality failures can occur (with variation of source temperature). Such variations can be easily adopted though primary flow adjustment or opening factor.

Fig. 10. Feed temperature at various primary pressure for different nozzle opening.

Fig. 11. Maximum Flux at various primary pressure for different nozzle opening.

Fig. 12. Surface plot on Suction capacity at different inlet pressure for mixing chamber to throat diameter ratio.
The maximum secondary flow handling capacity of such kind of system is represented in Fig. 10. This Eductor based membrane distillation system can handle mass flux of up to 17 kg/sec, for sensible cooling with primary flow $\Delta T$ of 5 $^\circ$C. Increasing cross sectional area increases the mass flow of primary fluid (cooling fluid) and hence, condensation and sensible cooling of higher mass flows becomes possible. The prime objective of modification of this part is to introduce the operational flexibility of the system, such that change in operational condition of feed, is adopted with Eductor primary pressure and nozzle opening hence, make it more sensible and flexible for application in Membrane Distillation Process.

4.3. Effect of area ratio

In Eductor (Fig. 5), area ratio ($A_R$) is the ratio of the cross-sectional area of the primary nozzle to mixing chamber entrance (Eq. (11)).

$$
A_R = \frac{A_3}{A_4}
$$

Low pressure higher flow ratio around 0.1

$$
A_R = \frac{A_3}{A_4}
$$

Higher pressure and low flow ratio around 0.6

\[(11)\]

Fig. 13. Nature of primary jet core at different $A_R$.

Fig. 14. Feed temperature with respect to inlet pressure at different area ratio.

Fig. 15. Nature of swirling flow in a pipe.
It is the prime feature determining the performance characteristics, with identical performance curves in systems having the same $A_R$ (Lea et al., 2008). Typically, the value ranges from 0.02 to 0.9 with low pressure and high flow ratio around 0.1 and high pressure and low flow ratio around 0.6. The area ratio is related with mixing chamber opening, which plays an essential role in its application for water desalination system. It deals with momentum transfer between primary and secondary fluids, which also performs two-fluid mixings and heat & mass transfer where feasible. This study on analysis of performance based on $A_R$ further aids in understanding the phenomenon.

Here study case is an Eductor operating in low pressure and higher flow ratio region, the effect of variation in flow ratio on typical Eductor is shown in Fig. 11. The variation in diameter of the mixing chamber ($d_4$) has been considered, to adhere to the study. At a value of $A_R$ with an increase in inlet pressure and vice versa increases the suction capacity of the system. For both cases, increment bands are higher at higher values. From another perspective, at a constant value of $A_3$, lowering the value of $A_4$ increases the suction capacity, but the selection of optimum value based on manufacturing and operational feasibility and structural acceptability is essential.

Fig. 12 is the velocity contour from the nozzle to throat inside Eductor, at four $A_R$: 0.14, 0.17, 0.19 and 0.23. It can be noted that the primary core length of jet increases from 80 to 86 mm with increasing $A_R$. The diffusion region was also found to increase from 97 to 110 mm. With an increase in jet influential length, the resultant increase in momentum transfer increases the suction capacity of the system Fig. 13.

Feed temperature and maximum flux at various primary pressure of Eductor are shown in Fig. 14 and Fig. 15 respectively. In the study range, feed temperature of up to 20 °C can be utilized when area ratio is 0.25. The allowable limit of mass flow rate for cooling capacity is constant and related with inlet pressure. Increasing primary pressure ultimately increases the secondary pressure due to energy conversion ratio in primary nozzle and hence lower temperature feed sources becomes feasible. Increasing Area ratio, here in this case though variation of mixing chamber size, also increases the potential of low temperature source utilization. Larger ratio refers to smaller chamber inlet, with condensing secondary flow this can have an added advantage of lower shear stress and hence better entrainment.

4.4. Effect of inlet swirl

Fluid flowing with the axial and tangential component is swirling flow, they form circular twisting path during the process. Fig. 16 shows the nature of swirling flow from the inlet into a circular pipe. The twisting nature of streamline and their radial nature at surfaces 1 and 2 has been presented for better understanding of phenomenon. The flow swirl is described through tangential, axial and radial components as presented Fig. 17.

Swirl at inlet has an extended effect on two-phase mixing, as traveling time in the mixing zone increases. The larger interaction time enhances better mixing and thermal property exchange. This study focuses the influence of this increased interaction time on
suction capacity of eductor. These swirls can be generated using guide vanes, at the primary nozzle exit. Swirls in this study were defined with a cylindrical coordinate system (radial, tangential and axial components). Axial flow component forms primary recirculation zone predominant by primary inlet flow rate. The tangential component generates swirl along with subsequent out-of-plane shear stress in the flow (Clean Combustion Research Group, 2018). The weak or moderate swirl with $S_R < 0.5$ were introduced for this study (Dartmouth College, 2018). The available energy i.e. inlet boundary condition was truncated to axial and tangential components using Eq. (9), constant interval computations were performed with comparison factor of dimensionless number; Swirl Ratio, from Eq. (10).

$$v_r^2 + v_	heta^2 = 1 \quad (9)$$

$$S_R = \frac{v_r}{v_0} \quad (10)$$

Fig. 15 is the surface plot for computational results of suction pressure, defined as a function of inlet pressure and swirl ratio. For different inlet pressure, increasing swirl ratio decreases maximum suction capacity of the system. The highest suction capacity was noted for zero swirl ratio, in each of the pressure inlet conditions. The higher suction capacity is expected for the application. The bandwidth of decreasing suction capacity for different inlet pressure conditions tends to be narrow with increasing swirl ratio.

5. Conclusion

This work proposes Eductor as a combined vacuum generator and condenser, replacing bulky vacuum pumps and indirect heat exchangers in thermal desalination processes, specifically membrane distillation. Primary & secondary pressure of Eductor, minimum brine feed temperature & maximum allowable total flux (secondary flow in Eductor) are major metered parameters. Additionally, it’s significance and practicality for proposed process, with influence of geometric (Area Ratio and primary nozzle opening) and operational (primary flow pressure & nature) parameter variation were examined.

The computational and experiment result shows increase in primary pressure increases the suction capacity of Eductor. The inlet swirls provide additional time for mixing and heat transfer but has negative impact of swirl ratio on suction pressure. This limits the suction source operational temperature and mass flow.

The performance of Eductor is significantly affected by geometry. The increasing $A_R$ increases the influencing length of jet and hence increases the resultant vacuum pressure. Primary pressure variation influences the output, hence feedback-based positioning of spear valve in primary nozzle can complement immediate need, since VMD is pressure sensitive system. At general operating conditions, adaptation to fluctuation is limited hence with geometric flexibility operational range can be widened.

Thermodynamically, minimum required feed temperature and maximum allowable secondary mass flow rate are also the function of Eductor geometry and operating condition. The higher primary pressure allows lower temperature feed source and higher secondary mass flow. The feed temperature variation can be compensated with nozzle opening. Larger nozzle opening allows higher cooling capacity, hence can have sensible cooling of larger secondary mass flow. For larger $A_R$, it allows lower temperature feed, this might not be directly related in increasing the cooling capacity but can lower interphase shear stress and hence can achieve larger pressure recovery and better condensation.

The flexible thermodynamic and suction performance of Eductor suggests it, as a good option in simplifying existing thermal desalination processes. Although the proposed primary focus is on reduction of footprint & development of simple system, Educators can have wider applications in sensitive fluid mixing, direct contact condensation, pumping, and delivery systems. This work is equally important in all the other domains as well. The flexibility with minor modification can widen application of Eductor. Associated future work should be focused on two-phase flow, design optimization, and application-based performance.

Declaration of Competing Interest

The author declares no conflict of interest.

References


