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# Performance Prediction and Experimental Investigation of Swirl Atomizer for Evaporation of Water at Low Pressure

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**Abstract**

This paper describes the swirl Injector performance which finds application in the low temperature sea water spray flash vaporization desalination system. The saline water was sprayed into the vaporizer as fine droplets using a swirl Injector and evaporated at the low pressure. The maximum flow rate was 3600 lit/hr. The injector performance was determined for different feed water temperatures, Vacuum and water injection pressures. Low Pressure Flash Evaporation desalination experiments were conducted by using swirl injector. The effects of atomizer's dimensions and flow parameters were studied and analyzed to get desirable droplet size and good yield. From this parametric study, it is established that droplet diameter in the range of 700 to 900 μ m yields maximum. This result gives a valuable output for studying internal flow behavior in the swirl injector.

**Keywords:** Water spray, Swirl nozzle, Atomization.

## Introduction

In this paper the design, Performance, and experimental investigation of swirl atomizer (Injector) for the injection of water at temperatures between $26^0$C and $32^0$C is investigated experimentally, which finds application in the low temperature sea water desalination system [1] and OTEC system [2],which follows spray flash evaporation. Not much work has progressed in the field of spray flash evaporation.Muthunayagam. A.E [1], introduced a new concept for sea water desalination, where warm ocean water from the upper strata of the ocean in the ambient temperature is injected (sprayed) into a flash evaporator at a low pressure and the resulting water vapour is condensed in a condenser, using the cold ocean water taken from the depth of the ocean. Swirl injector is selected for injecting the feed water in to the vaporizer.

During the past decade there has been tremendous knowledge generation in the field of atomization, which is now developed into a major interdisciplinary field of research. The growth of interest has been accompanied by large strides in the area of spray analysis and in a proliferation of mathematical model for spray process. It has become increasingly important for engineers to acquire a better understanding and limitations on all the relevant atomization devices.

Many work progressed in the area of swirl atomizer design. But all the works are with low flow rate and high pressure drop. But for spray flash evaporation high flow and low pressure drop is expected [1], no such nozzle design was reported in the literature.Mikkel S.Nilars [3] explained about design of full cone nozzle and liquid atomization process in full cone nozzle. He has explained about various configuration of nozzle orifice arrangement. Masahide Takagi [4] considered the primary atomization model, where the conical liquid sheet at the nozzle exit consists of coherent initial ligaments which disintegrate into primary droplets at the location which is determined by linear stability considerations.

Pressure swirl atomizers are constructed with hollow cone structure, fine atomization with good spray character. It gives smaller droplets and larger axial velocity. Liquid sheet formation and generations of droplets and spray angles results in a modeling of swirl type injector [5-7].

## Parameters Affecting Mean Droplet Size of Swirl Injector

Various types of injector which give better atomization and various categories of disintegration of liquid sheet which directly depend on flow parameters. The design parameters of swirl Injectors are explained in [8]. In swirl injector the liquid enters in to the injector through a channel, which is tangential to the axis of the injector. Thus swirl injector is imposed on the liquid. Under the action of centrifugal force, the liquid spreads out in the form of a conical sheet as soon as it leaves the nozzle, and a hollow cone spray is formed due to breakup of the sheet.

The effect of various parameters on disintegration of the liquid sheet is discussed here. The design parameters include Liquid properties, Nozzle Pressure Differential, Geometric parameters of the injector. Geometric parameters include Diameter of swirl chamber ($D_s$), Length of the swirl chamber ($L_s$) depth of exit orifice, Diameter of discharge orifice ($d_o$), Diameter of Tangential inlet orifice ($d_p$), Length/Diameter ratio of swirl chamber ($L_s/D_s$ ratio), Length/Diameter ratio of final orifice ($l_o/d_o$ ratio) swirl chamber, Ratio of swirl chamber diameter to final orifice diameter ($D_s/d_o$ ratio), Ratio of Length to diameter of swirl port.

At the injector exit, the flow through the orifice becomes a free sheet that later forms the spray. This important boundary, along with the aerodynamic interaction with the ambient gas, determines the behavior of the spray. Thus knowledge of the flow field at the injector exit is necessary for spray prediction.

## Design Consideration of Swirl Injector for High Flow

The following Design conditions are taken for designing the high flow swirl injector;

Mass flow rate ($m_l$) =1lit/s
No of inlet orifices (i) = 1 no
Density of water ($\rho_l$) = 1000 kg/m$^3$
Mean drop size = 700 -900µm

Frictional losses are major considerations in the design of swirl injectors. The following equations are used to calculate the mean droplet size of the droplet.

Discharge coefficient ($C_D$):

$$C_D = 0.35\left(\frac{A_p}{D_s d_0}\right)^{0.5}\left(\frac{D_s}{d_0}\right)^{0.25} \tag{1}$$

(Ref: 8: Page264 to 267)

Diameter of orifice discharge ($d_o$):

$$d_o = \sqrt{\frac{4m}{\Pi \mu_d \sqrt{2\rho \Delta p}}} \tag{2}$$

Diameter of Tangential inlet orifice ($d_p$):

$$d_p = \sqrt{\frac{2 R d_0}{i K}} \tag{3}$$

Corrected diameter of Tangential inlet orifice ($d'_p$):

$$d_p^1 = \frac{d_p}{\sqrt{\varphi}} \tag{4}$$

$$\sin\theta = \frac{\pi (1 - x)^{1.5}}{2k(1+\sqrt{x})(1+x)^{0.5}}$$

$$x = \frac{(d_o - 2t)^2}{d_o^2} \tag{5}$$

$$t(\text{film thickness}) = 3.66\left(\frac{d_0 m_l \mu_l}{\rho_l \Delta P_l}\right)^{0.25} \tag{6}$$

Mean Droplet Diameter (D):

$$D = 2.47 m_l^{0.315} \Delta P_L^{-0.47} \mu_L^{0.16} \mu_A^{-0.04} \sigma_l^{0.25} \rho_L^{-0.22} \left[\frac{l_0}{d_0}\right]^{0.03} \left[\frac{L_S}{D_S}\right]^{0.07} \left[\frac{A_P}{D_S d_o}\right]^{-0.13} \left[\frac{D_s}{d_o}\right]^{0.21} \quad (7)$$

(Ref: 9:page no 215 to 218)

Diameter of swirl chamber $(D_s) = 2R + d'_p$ (8)

Length of the swirl chamber $(L_s) = 2x \times d'_p$ (9)

(Ref:8: page no 266)

Where,

$\Delta P_L$ -- Pressure difference in liquid
$\mu_L$ --- Dynamic viscosity of liquid
$\mu_A$ ---dynamic viscosity of air
$\sigma_l$ -- Surface Tension of liquid
$D_s$ — Diameter of swirl chamber
$L_s$ — Length of swirl chamber
$d_0$ — Diameter of cylindrical exit orifice of atomizer
$A_p$ — Cross Section Area of Tangential inlet Orifice
D – Mean Droplet Diameter
$d_o$ --- orifice discharge diameter(m)
$m_l$ --- mass flow rate(lit/s)
$\mu_l$ --- Dynamic viscosity (Nm/s)
$\rho_l$ --- Density of liquid (kg/m$^3$)
$\Phi$ ---Contrication coefficient
$\chi$ ---Ratio of area of inlet ports to area of final discharge orifice.
K -- Geometric constant.
$d_o$ --- Orifice discharge diameter (m)
t --- Liquid film thickness (mm)
$A_p$ -- Total cross-sectional area of inlet port
$D_s$ -- Diameter of swirl chamber (mm)

In the above equations some the values are taken from [9], they are listed below. The value of $D_s/d_o$ ratio should be kept small to reduce frictional losses and suggested that $D_s/d_o$ ratio should not exceed 5.0 and the $L_s/D_s$ ratio lies between 0.5 and 1.0.Similarely Length to diameter of swirl port ratio should not be less than 1.3 and $l_o/d_o$ ratio should be around 0.5 with $\Phi$ as 0.9.With the help of the above values the droplet diameter is calculated for different Pressure drop ($\Delta$p)= 0.5, 1, 1.5 and 2 bar and Geometric constant (K) = 0.5, 1.0, 1.5, 2.0.Therefore the following graphs where obtained when we do the calculation, this will be useful when selecting the best nozzle.

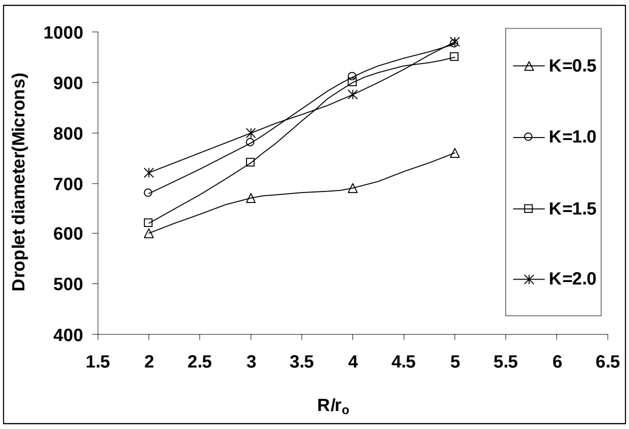


**Figure 1:** Variation of droplet diameter with R/$r_o$, for different K value at 0.5 bar injection pressure.

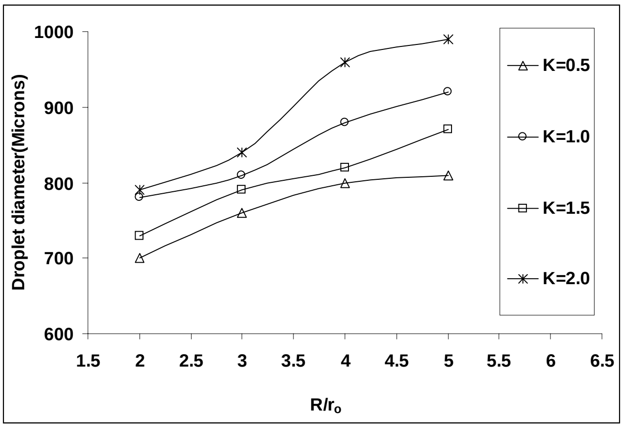


**Figure 2:** Variation of droplet diameter with R/$r_o$, for different K value at 1.0 bar injection pressure.

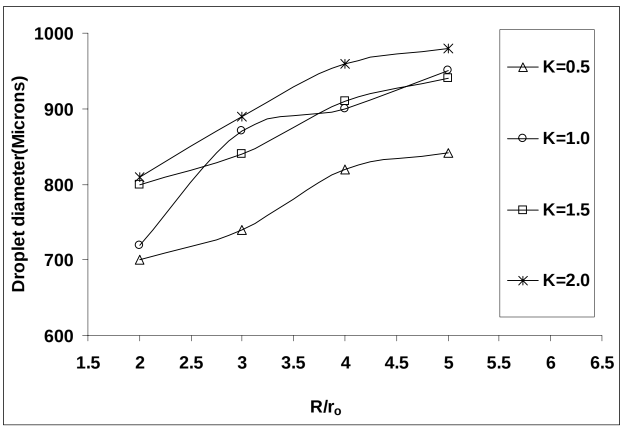


**Figure 3:** Variation of droplet diameter with R/$r_o$, for different K value at 1.5 bar injection pressure.

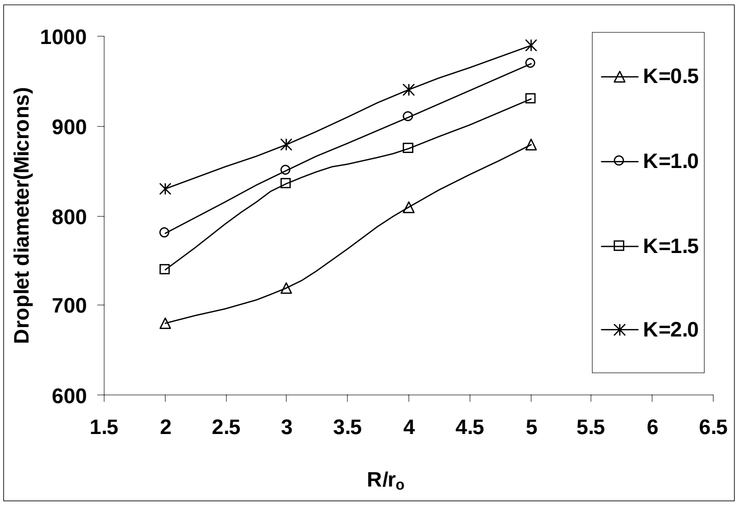


**Figure 4.** Variation of droplet diameter with R/r$_o$, for different K value at 2.0 bar injection pressure.

Considering the above-mentioned point, the injector which gives the lowest droplet diameter, is considered for fabrication.Figure.5, shows the fabricated injector.

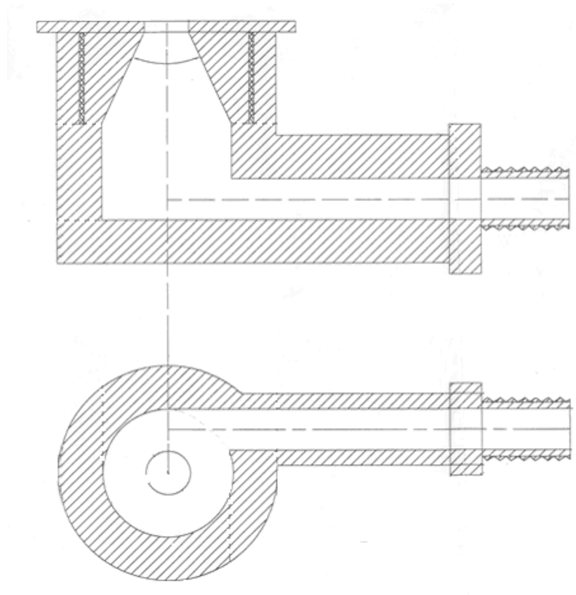

**Figure 5:** View of swirl injector injector.

## Description of the Experimental Facility

There are two types of experimental facility; one is for testing the injector droplet size; which is shown in figure.6, and the other is for testing the injector in low pressure vaporizer to study the vaporization characteristics; which is given in figure.7. The feed water system in figure.1consists of a 2 $m^3$ storage tank, from their water is pumped to the swirl injector, which is kept in the injector stand as shown in the fig. 6.

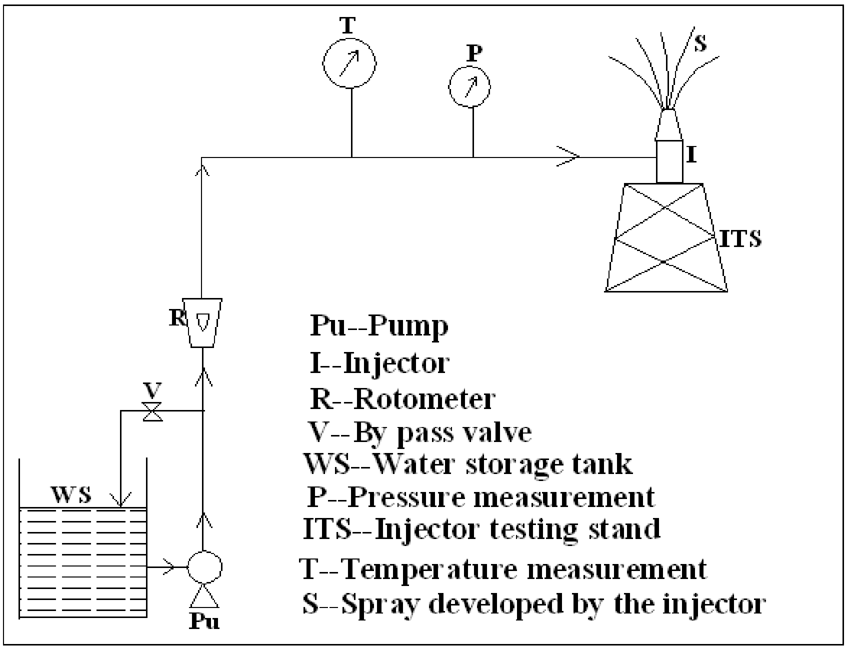


**Figure 6:** Experimental facility for injector testing.

Four different configurations of tangential swirl injectors are designed, fabricated and tested in low pressure medium. For varying the Inlet temperature, pressure and various low pressure outlet conditions, the test was conducted. The droplet size was measured by mechanical methods. Allow the spray droplets fall in to the smoke deposited glass plate and the average droplet size was measured with the help of microscope. The main function of atomizers is to transform liquid to fine droplets and to increase the ratio of surface area to volume to promote evaporation. They usually generate good atomization with higher relative velocity between liquid and environment .Suitable geometry design of atomizers will get good atomization. In this work, a theoretical study is attempted to evaluate the geometrical parameters and its effect on the atomization.

In figure 7, the vaporizer used is of circular cross-section of diameter 600 mm diameter and 1000 mm height.

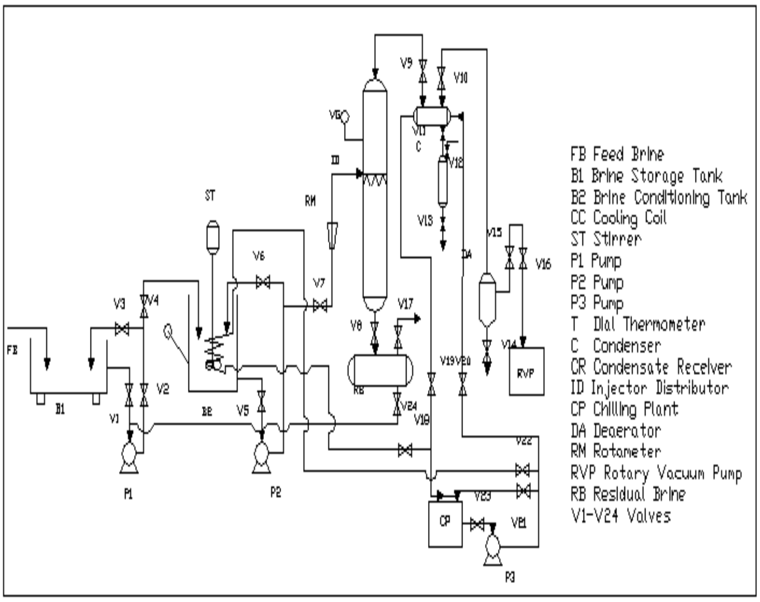


**Figure 7:** Experimental facility for studying vaporization characteristics.

## Performance of Swirl Injector

The atomization is best when the droplet diameter is small. The design model is given below.

The Pressure- swirl atomizers the liquid emerges from the nozzle as a thin conical sheet that rapidly attenuates as it spreads radially outward, finally disintegrating into ligaments and then drops. In the prefilming air blast atomizer the liquid is also spread out into a thin continuous sheet before being exposed to the high velocity air. It is of interest, therefore, to examine the factors that govern the thickness of this liquid film. The primary droplet diameter is assumed proportional to the local liquid sheet thickness. Injection characteristics such as spray penetration, mean droplet size, and volume distribution have been carried out.

The spray angle decreased with increasing injection pressure. In figure 8.Variation of film thickness with injection pressure drop is plotted.

The spray angle decreased with increasing injection pressure. The average size of droplets decreased with decreasing environment in as injection pressure increases, which is seen from the figure.9.

Atomization quality is usually described in terms of a mean droplet size. Because the physical process involved in atomization are not well understood, empirical equations have been developed for expressing the mean drop size in a spray in terms of liquid properties, flow properties and atomizers dimensions. The function of atomizer is not only to disintegrate a bulk liquid into small droplet size, but also to integrate these drops into the surrounding in the form of symmetrical uniform spray. Exit orifice diameter affects the rate of atomization.

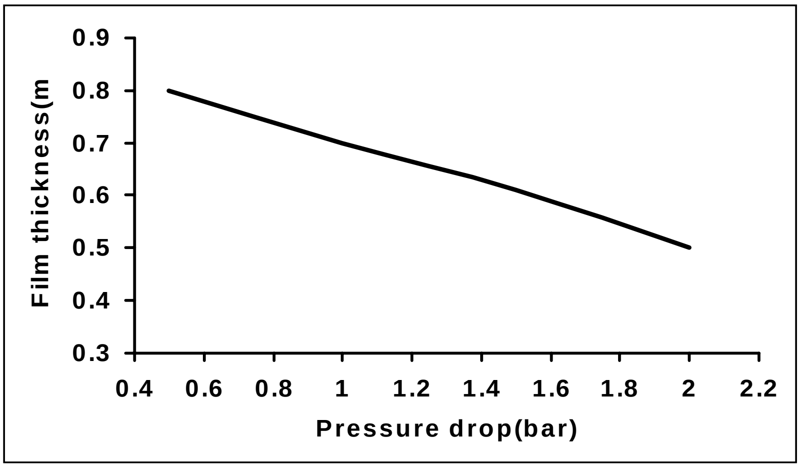


**Figure 8:** Variation of film thickness with injection pressure drop.

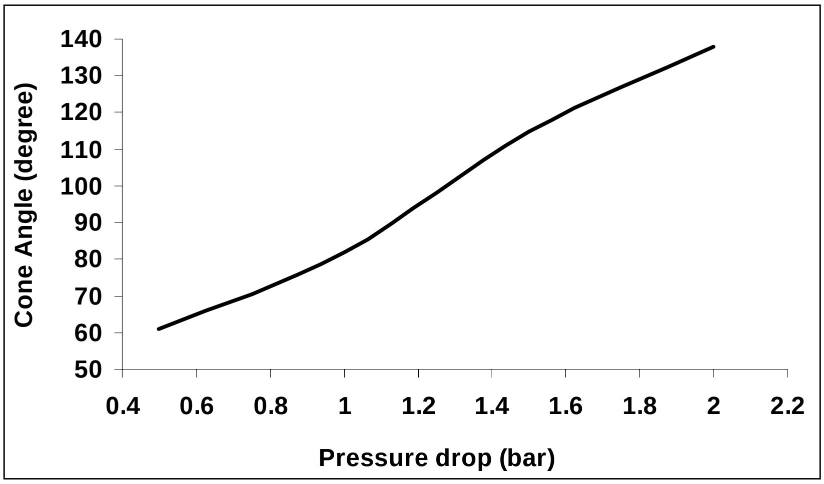


**Figure 9:** Variation of cone angle with pressure drop.

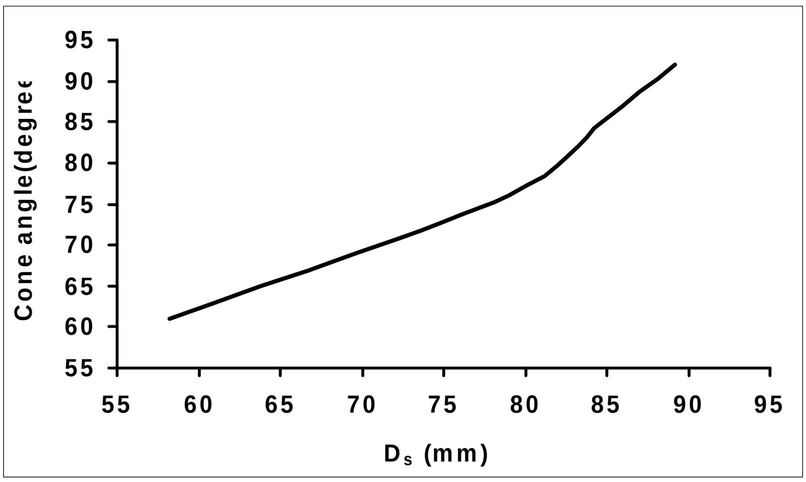


**Figure 10:** Variation of cone angle with droplet size.

**Flow Velocity:** When the flow velocity is high, droplet diameter becomes small, due to better atomization. Initially when the flow velocity increases, drop size decreases very drastically.

**Liquid properties:** In practice the significance of surface tension is diminished by the fact that most commercial fuels exhibit only slight difference in this property. However viscosity varies by almost two orders of magnitude in some applications, so its effect in atomization quality can be quite large in some specific cases.

**Nozzle Pressure Differential:** Increase in liquid pressure differential causes the liquid to be discharged from the nozzle at a higher velocity, which promotes a finer spray. By raising the nozzle pressure differential, the atomization quality can be improved.

**Atomizer Dimensions:** The most important thing for atomization is the thickness of the liquid sheet as it leaves the final orifice. The mean drop size is roughly proportional to the square root of liquid sheet thickness. The increase in atomizer size will reduce the atomization quality.

**Length/Diameter Ratio of swirl chamber:** The atomization quality improves initially with an increase in Ls/Ds ratio.

## Result and Discussions

Quantitative relationships is in between the atomizer dimensions and various flow parameters, such as discharge co-efficient, film thickness, spray cone angle and etc.,The fabricated swirl injector is tested in the available desalination plant by providing rapid means of sampling and counting. Automated data acquisition and processing are needed to get the results in seconds. The discharge co – efficient of a swirl atomizer is inevitably low. The effect of viscosity is to thicken the fluid film in the final orifice and they help to increase in discharge coefficient. The following expression is used to calculate discharge co efficient

Theoretical relationship between co- efficient of discharge and atomizer dimensions with respect to is $D_s$ / $d_o$ was illustrated as below. In pressure swirl atomizers, the liquid emerges from the nozzle as a thin conical sheet that rapidly attenuates as it spreads radically outward, resulting in disintegration into ligaments and then drop. Thickness of liquid film should be low.

Increase in final orifice diameter leads to a thicker film. This is because increase in orifice discharge leads lowers $C_d$. The effects of a reduction in swirl chamber diameter are to increase the liquid film thickness. The effects of orifice length and swirl chamber length on film thickness are quite small.D (droplet size) is compared with film thickness. If film thickness increases droplet diameter ‘D’ also increased. So thickness of film should be minimum for smaller diameter of droplet.

The spray angles produced by pressure swirl nozzles are of special importance their application to desalination systems. Spray cone angle is determined solely by the swirl chamber geometry and is a unique function of the ratio of the inlet ports area to the product of swirl chamber diameter and orifice diameter $A_p$/ $D_sd_o$.

When the orifice diameter and pressure drop improves, cone angle (2 θ) will be increased. But for good atomization, cone angle should not exceed 60-90, because spray formation depends upon cone angle and orifice diameter. The variation of cone angle with swirl chamber diameter is shown below.

If (Ds) diameter of swirl chamber is large, cone angle becomes high, at ΔPl = 0.5, 1.0 bar and for cone angle in between 60-90. This gives good atomization. So, minimum droplet diameter is obtained at the range of pressure drop 0.5 and 1.0 bar.

An experimental study is conducted with the few conducted experiments and the result gives a valuable output for developing further high flow swirl injector that gives good atomization. The design feature detailed here may positively help to attain the high flow rate. A parametric study on the effect of operating and design parameters on the performance of swirl injector was carried out. Experiments are conducted with the designed nozzle at 14 and18 mm of Hg, which are given in figure.14 and 15.

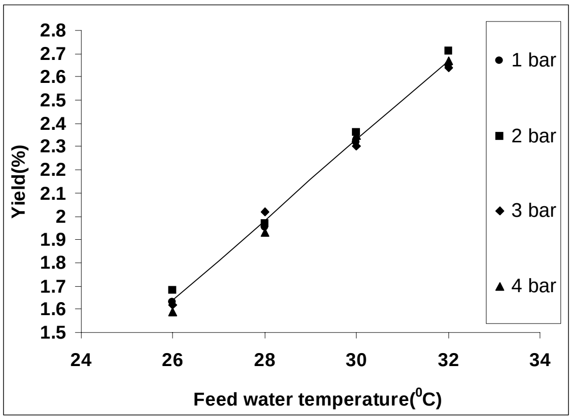


**Figure. 11:** Comparision of theoretical yield with experimental value for a vaporizer pressure 14 mm of Hg.

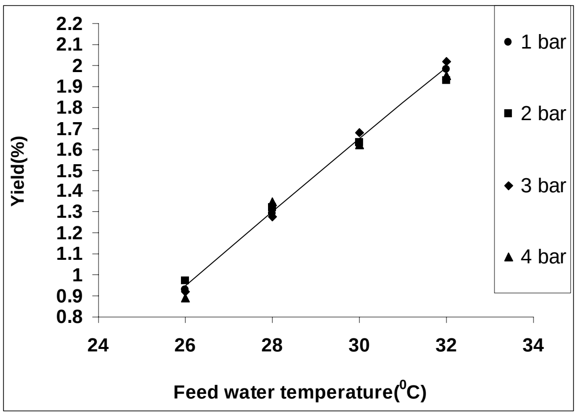


**Figure12:** Comparision of theoretical yield with experimental value for a vaporizer pressure 18 mm of Hg.

## Conclusion

Increase in spray cone angle reduces mean drop size. An increase in spray angle should cause stronger dependence of mean drop size on both viscosity and pressure differential $\Delta P_L$.The spray angle not only improves atomization quality but also increases the dependence of mean drop size on both viscosity and liquid injection pressure. That the exponent of $\Delta P_L$ increases with increase in viscosity.

As liquid density influence on mean drop size should generally be quite small .The impact on mean drop size of changes in nozzle dimensions and operating conditions will vary depending on the level of liquid viscosity. The liquid of high viscosity mean drop size will be more dependent on injection pressure differential $\Delta P_L$ and less dependent on nozzle flow number and spray cone angle than liquids of low viscosity. Further studies can be made to develop injection systems with very high flow nozzles or with more number of nozzles to develop commercial desalination plants. The results indicate the need for a detailed study of the flow characters of the nozzle and to establish a correlation between the nozzle configuration, the injection pressure and the droplet size of the particles. However the increase is not substantial but it is well.

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