Experimental Analysis and Mathematical Modeling for Minimum Water Quantity Required in Dishwasher

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Abstract : Dishwasher is the device used to wash dishes as well as other kitchen utensils. Water distribution system of dishwasher, impacts the water jet on utensils. It cleans them by striking water jets at different angles on the surfaces of the utensils. Centrifugal pump is used as driving unit to circulate water into the system. During washing phase, certain amount of water is taken into dishwasher and fed to pump to carry out washing process. Amount of water used in washing is one of the factors that decide rating of dishwashers, so it is essential that it should consume minimum water. But, if water is taken below certain amount, pump in dishwasher becomes unstable. Objective of this paper is to find out the minimum water amount that must be there in a dishwasher by mathematical modelling in Dymola software so that pump will not become unstable. Validation is done with results obtained from experimentation.

***IndexTerms* - Mathematical modeling, pump stability, dishwasher, minimum fill, Dymola**

I. INTRODUCTION

Dishwasher is a machine that washes kitchen utensils by striking high speed jet of water on dirty surfaces of the utensils. Dishwasher mainly constitute of water distribution system, racks, heater, sump, tub structure, sidewalls, detergent dispenser etc. Water distribution system consists of motor, pump, manifold, filter, spray arms and sump. A centrifugal pump is used as driving unit to circulate water into the system. From centrifugal pump water is further pushed to manifold and then to spray arms. Spray arm is designed in such a way that when pressurized water comes into spray arm it start to rotate. Spray arm has got small nozzles over its surface with different angles through which a high speed jet of water is made strike on utensils kept in racks. Angles of the nozzles on spray arms are such that water strikes on all surfaces of utensils. As a result dishes get cleaned. Also temperature of water is increased and detergent is used so as to get good washing performance. Amount of water consumed by dishwasher per year is one of the factors that decide its rating.

So it is essential for manufacturers to ensure that dishwasher will consume as much less amount of water as possible. In a particular washing phase water amount taken into dishwasher is already defined in the washing cycles. User just needs to select cycle and dishwasher will take amount of water already defined by cycle design engineers into that cycle. Pump stability is the limit for taking minimum amount of water into dishwashers. It must take amount of water that will ensure pump stability. Minimum amount of water that ensures pump stability in a dishwasher is termed as minimum fill. If water amount taken is less than that of minimum fill amount then pump will be unstable which cause increase in noise and vibration level. Also due to unstable working of pump, life of pump components decreases.

Minimum fill quantity is obtained as per tests are carried out by cycle design engineers. These tests are time consuming as well as resource consuming. If the minimum fill amount can be found out directly by mathematical model, it will save time, money as well as resources. Objective of this paper is to find out the minimum water amount that must be there in a dishwasher so that pump will not become unstable by mathematical modelling in Dymola software.

II. NOMENCLATURE

H Head developed by pump in m
N Speed of impeller in rpm
Q Discharge in m^3/s
K Coefficient of loss of head in impeller and casing
D_2 Diameter of impeller at outlet B_2 Width of impeller at outlet
ϕ Angle made by relative velocity with direction of motion of vane at outlet
g Acceleration due to gravity

III. LITERATURE REVIEW

The intensive study has been made by different scientists in the field of pump performance, system resistance, pump modelling, pump instability, dishwasher distribution system and effect of cavitation on performance of pump.

Johann Friedrich Gulich [1] did huge study on fluid mechanics and hydraulic machines which also include study of centrifugal pump and phenomena regarding centrifugal pump along with cavitation. Study described cavitation phenomenon, precautions to be taken against cavitation and effects of cavitation on centrifugal pump. Study also included the effect of air on the performance pump.

Denghao Wu et al [2] investigated pressure pulsation and flow instabilities in a centrifugal pump at part load conditions. In investigation pressure pulsation were extracted at 6 different locations inside the centrifugal pump around the volute under different flow rate conditions ranging from 10% to 120% of the nominal flow rate. Study led to the conclusion that the pressure pulsations are exclusively induced by the flow instabilities, especially the vortices in the flow passage of the impeller. At the nominal flow rate pulsation found with least amplitude and as flow rate moves away from the nominal flow rate, amplitude found to be higher.

J. F. Guelich and U. Bolleter [3] described pressure pulsation in centrifugal pumps, physical mechanism causing pressure pulsation, characteristics of the pressure pulsations, effect of pressure pulsations and methods to scale pressure pulsation. From study it can be concluded that pressure pulsations in centrifugal pump are created by the wake flow from the impeller blade trailing edge and by large scale turbulence and vortices generated by flow separation and flow recirculation at part load.

Dazhuan Wu et.al [4] studied experimentally hydrodynamic performance of a cavitating centrifugal pump during transient operation. They carried out experiment in order to analyze the cavitation of a centrifugal pump and its effect on transient hydrodynamic performance during transient operation. They done study by changing suction pressure and acceleration and came up the conclusion that pump undergoes cavitation at low suction pressures during starting period.

Mohammed Ahmed El-Naggar [5] did one-dimensional flow procedure for analytical study of centrifugal pump performance by applying the principle theories of turbo machines. The procedure adopted had ability to obtain performance characteristics of the pump in dimensionless form. Predicted performance characteristics were found to be consistent with the experimental results.

IV. OBJECTIVE AND METHODOLOGY

The objectives of the project are as follows:

1. To find out minimum fill amount and factors affecting minimum fill amount in a dishwasher experimentally.
2. To develop a mathematical model for minimum fill amount in a dishwasher
3. To validate mathematical model result with experimental result.

Following activities are carried out to accomplish objectives mentioned above:

1. Working of dishwasher, washing phenomenon, water distribution, minimum fill amount and factors affecting minimum fill amount are understood visually by performing experiments and from literature review.
2. Flow rates, velocities and pressure losses in each component are found out mathematically.
3. Experimentation was done to find out minimum fill amount, factors affecting minimum fill amount in a dishwasher and to find out flow rate of water returning to dishwasher after circulating through the water distribution system.
4. Mathematical model is developed for minimum fill amount consisting of following sub models:

a. Model to obtain operating point of pump in a dishwasher (by use of sub models for pump performance and system resistance)

b. Model to obtain minimum fill amount in a dishwasher (by use of model for operating point and experimental results obtained for factors affecting minimum fill amount)

5. Validation of the model result value for minimum fill amount is done with experimental value.

Working of dishwasher is analyzed by visual inspection and found that there are four factors that are to be combined to get minimum water quantity required in a dishwasher, which are water volume stored in distribution system, flow lag due to difference between flow rates going in and coming out from distribution system, water retention on various components of dishwasher and time lag volume. To reach final objective i.e. to get minimum water amount required, methodology opted is discussed in following paragraphs.

Overall representation of plan executed to reach ultimate objective i.e. obtaining minimum water required in a dishwasher is shown in Fig. 1.

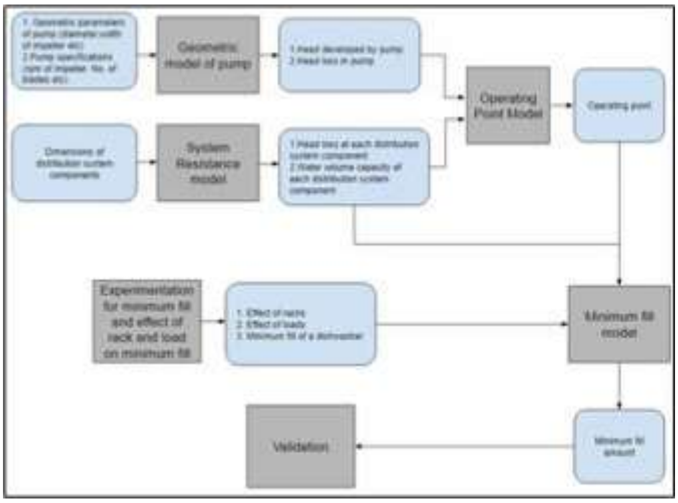

Fig.1. Execution plan opted to obtain minimum fill amount.

A. Mathematical Model to Get Operating Point of the Pump in Dishwasher

Operating point of the pump is obtained from intersection of pump performance curve and system resistance curve. So first both those curves are need to be obtained. 1. Pump performance curve with air entrainment effect Mathematical model that give pump performance is developed in Dymola software. Head developed by the pump is found out by formula,

$$H=AN^2+BNQ+CQ^2 \quad (1)$$

Where,

$$A=\frac{2k_1^2-KK_1^2}{2g} \quad (2)$$

$$B=\frac{K_1K_2K_3-2K_1K_3}{2g} \quad (3)$$

$$C=\frac{KK_2+KK_3}{2g} \quad (4)$$

$$K_1=\frac{\pi D_2}{60} \quad (5)$$

$$K_2=\frac{1}{\pi D_2 B_2} \quad (6)$$

$$K_3=\frac{1}{\pi D_2 B_2 tan\emptyset} \quad (7)$$

Results obtained from the model are well correlated with the pump performance data taken from supplier (Nidec Co.). In operating flow range of pump in a dishwasher (i.e. 0.0004 to 0.00055 m3/s), maximum error given by model was found to be 3.73%.

Up to 10% air entrainment, it is possible to get effect of air on performance of pump by numerical analysis as up to 10% air entrainment, there will be a single phase flow and after that physics of flow becomes so complex that it cannot be determined numerical analysis [1]. In mathematical model inclusion of air effect up to 10 % is done.

2. System resistance curve

System resistance in a dishwasher water distribution system is obtained by dividing it into several parts. Depending upon shape of part it is assigned a generalized geometric shape to them. Fig. 2 shown below is showing actual water distribution system in a dishwasher and its representation with generalized geometries.

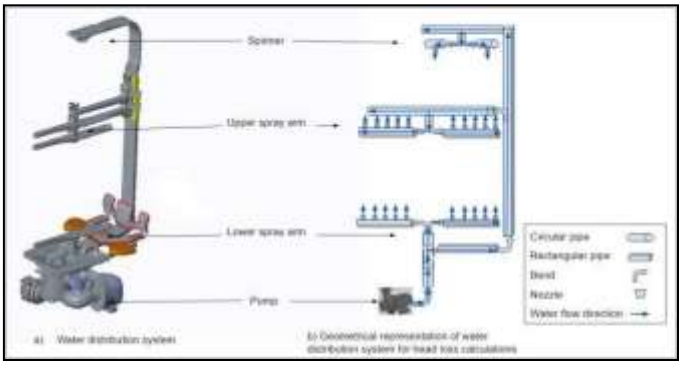

Fig. 2 Actual water distribution system and generalized geometric representation

System resistance for total water distribution system by using head loss formulae is shown in Fig 2. This is model is also developed to give water volume stored in each individual component of the water distribution system.

3. Operating point of the pump

It is the point of intersection of pump performance curve and system resistance curve. Pump performance curve and system resistance curve are plotted on the same graph to get operating point of the pump.

B. Experimentation for Volume Flow Lag

In dishwashers, at the start of washing phase, water going inside the dishwasher has high flow rate than the water returning at the entrance of pump. This is because, when water is come out of water distribution system it is made strike on utensils, racks or on walls of dishwasher. Due to this, water gets split into number of drops or small jets. Also some water is retained on the surfaces of utensils or walls of dishwasher. This returning flow rate increases with time and becomes stable when it comes in equilibrium with water going into pump. Due to this flow rate lag there is deficiency of water at the inlet of pump which need to be taken into account to get minimum water amount required in a dishwasher. This can be calculated by multiplying time lag with flow rate lag. Flow rate is nothing but the difference between water going into the pump and water returning to the inlet of pump after recirculation. Water flow rate going inside pump is the operating flow rate that is obtained from operating point model.

Water flow rate returning to pump inlet is obtained by experimentation which is very difficult to model numerically.

Pump is placed at the bottom of dishwasher in sump portion. Water is flowing from pump to upper spray arm and spinner and at last it is returns to sump. A plate is kept before the sump so that water gets collected into the plate instead of going to sump. For different time slots test is carried out and for that time slot flow rate is calculated. Time slots selected are 0 to 5 seconds, 5 tom 10 seconds, 10 to 15 seconds and last 15 to 20 seconds.

Experimental set up for the test carried out to get water flow rate returning to pump inlet is shown in Fig 3.

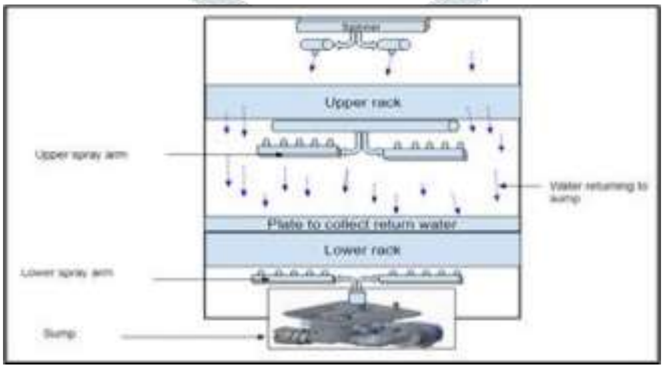

Fig. 3 Set up for return flow rate test

Flow lag difference in flow rates going into pump and returning into sump for each time slot is calculated. To get flow lag volume all the flow rate lags are added and multiplied by time.

C. Experimentation for Minimum Fill Amount and Factors Affecting Minimum Fill Amount

A standard test procedure is carried out to get minimum fill amount. Same test is replicated in lab to get minimum fill amount and factors affecting minimum fill such as racks and utensils and different utensil configurations. Following Fig. 4 is showing schematic representation of the test set up.

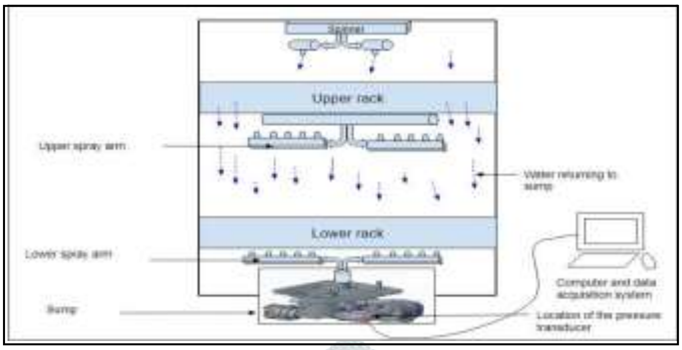

Fig.4. Schematic of experimental set up for minimum fill test

Minimum fill amount is decided on the basis of pressure fluctuations at the outlet of the pump. So, first of all pressure transducer is connected at the outlet of the pump. Some approximate amount of water is taken into the dishwasher and washing is started. Pump starts to circulate water through it and fluctuations at the outlet of pump are captured and recorded into the data acquisition system. Washing is done for 3 minutes and pressure fluctuation data obtained for 3 minutes is analyzed. If the peak to peak amplitude of pressure fluctuation is found to be less than or equal to 5 mbar, pump is said to be stable. If pump is unstable then 100 ml of water is added into dishwasher and procedure is repeated. Till pressure fluctuation magnitude get below 5 mbar, procedure is repeated. Water amount at which pressure fluctuation amplitude become 5 mbar, is said to be minimum water amount required in a dishwasher.

Same procedure is repeated to get the effect of lower rack, upper rack and different load settings (i.e. utensil configurations) and effect of each individual component is found out.

D. Minimum Water Amount Model

Using value obtained from above three models, minimum amount of water is found out by simply adding those quantities.

V. RESULT AND DISCUSSION

Specific output requirement are used to develop 4 models for experiment and each of them is discussed below:

A. Pump Performance Curves

Pump performance curve with pure water is obtained from model and compared with pump performance data taken form supplier (Nidec Co.). It is found to be well correlated over the wide range of flow rates. Within operating range of pump in dishwasher maximum error found to be 3.73 %. Following Fig. 5 shows comparison of model results with experimental results taken from supplier.

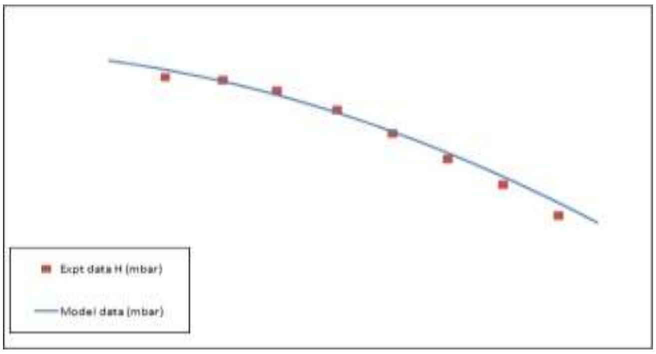

Fig.5. Validation of pump performance model

B. System Resistance Curves

Flow resistance of each component of is modeled and incorporated into single model to get resistance offered by whole water distribution system. Total system resistance is addition of flow resistance offered by system and static head. Following Fig.6 shows system resistance curve obtained from the model.

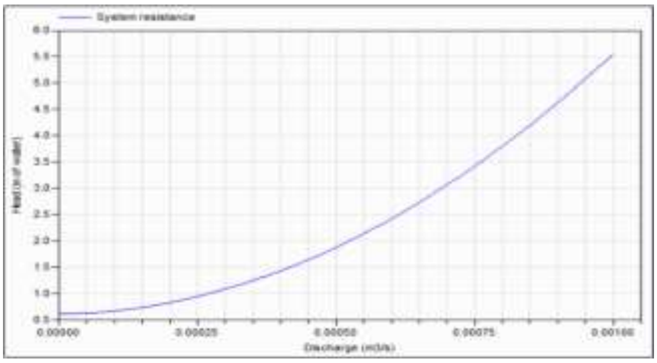

Fig.6 System resistance curve

C. Operating Point

Operating point is obtained by intersecting system resistance and system performance curve. Fig. 7 is showing operating point of the pump in a dishwasher obtained from the model.

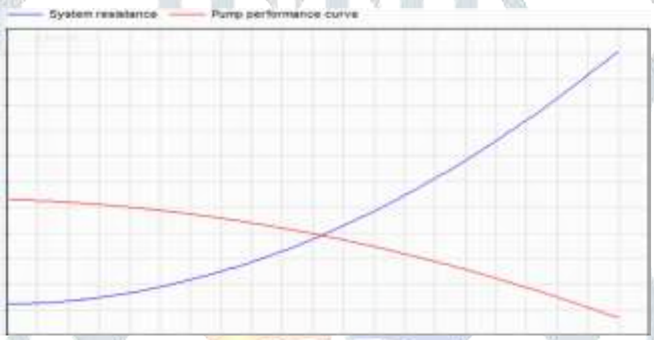

Fig. 7 Operating point of pump in a dishwasher

D. Experimentation for Flow Rate

Flow rate of water returning to sump in a dishwasher was initially found to be less and it goes on increasing with time and becomes stable when reaches to value equals to operating flow rate of the pump. Table 1 show results obtained from experimentation.

Table I. Flow rate of water returning to sump

Time	Total water in time in 5 sec	Flow rate (m^3/s)
0-5	1924	0.0003848
5-10	2225	0.000445
10-15	2439	0.0004878
15-20	2565	0.000513

E. Experimentation for Minimum fill and Factor Affecting Minimum Fill Amount

Experimentation is carried out as per standard test procedure. Results obtained from test are shown in Fig. 8 below. Test is carried out for different dishwasher configuration i.e. no rack, upper rack only, both lower and upper rack and then different place settings. Place setting is the configuration for the number of utensils placed. For example, 12 PS corresponds to 12 dishes, 12 cups, 12 glasses etc.

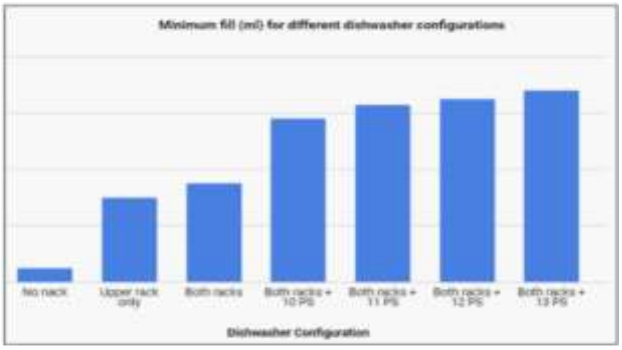

Fig. 8.Minimum fill and factors affecting minimum fill amount.

F. Minimum Fill Amount through Model and its Validation

Results obtained from previous models are used to obtain values for minimum fill contributors. Water amount stored in a water distribution system, flow lag volume, and volume of water required due to presence of different components like rack, load etc. are taken from previous models and by using them minimum fill amount for each dishwasher configuration, minimum fill amount is obtained. Minimum fill amount obtained from model in blue color and that obtained from experimentation in red color is shown in Fig. 9.

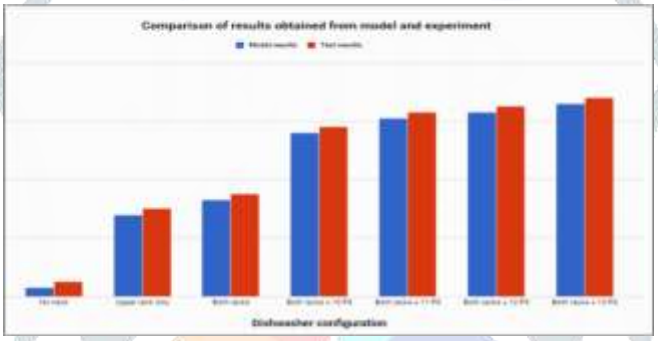

Fig.9. Validation of model results for minimum fill with experimental results.

From Fig. 9 it can be seen that as components are added into the system, minimum fill amount goes on increasing. Results obtained from model are in well correlation with the experimental results.

VI. CONCLUSION

1) Pump performance curve obtained from model is well correlated within operating flow rate range of the pump in a dishwasher. Maximum error found to be 3.73% within operating flow range.

2) Water amount stored in a dishwasher water distribution system, flow lag volume are contributing to the minimum fill amount. Also due to addition of each component like rack and different number of utensils, minimum fill amount get affected and it also contributes to minimum fill amount. 3) Air entrainment into the pump causes cavitation that causes flow rate to reduce, and due to this water may return to pump and as a result of this wash performance of pump decreases.

4) At the start of washing phase, water returning to sump has flow rate than that of flow rate of water going to pump. Flow rate of water returning to sump increases with time and become stable when it reaches to value equal to flow rate of water going into the pump.

5) Model developed for minimum fill amount can predict minimum fill quantity for different dishwasher configurations as well as for different water distribution systems. Also model able to predict minimum fill amount very close to the amount obtained from the experimentation.

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