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A SMALL-SCALE MULTIPLE EFFECT WATER DISTILLATION SYSTEM (MEWD) FOR RURAL SECTOR

Padma Vasudevan Sen[1] , P. K. Sen[2] , S.K.Vyas[3] , A. Mudgal[4]

[1] Centre for Rural Development and Technology, IIT, Delhi
[2]Department of Applied Mechanics, IIT, Delhi
[3]Indira Gandhi National Open University, Delhi
[4]Mechanical Engineering Department, CET (IFTM Campus), Moradabad
[1]padmav@rdat.iitd.ernet.in, padmav10@hotmail.com., [4]anurag_mudgal@yahoo.com.

ABSTRACT
A small scale multiple effect water distillation (MEWD) system for rural areas was designed and fabricated using locally available materials. The MED system was tested for its operation and performance for three effects and six effects using parallel, forward and mixed feed configurations. The unit is capable of delivering 60 to 100 litres of distilled water per hour. The unit employs falling film vertical tube evaporators and operates at supra-atmospheric pressure. Small sized orifices are used to withdraw distillate and brine. The unit is rugged and can be operated and maintained by rural artisans. The system was tested for its operation and performance. The total dissolved solids (TDS) content in the product water was found to be less than 20 parts per million (ppm). Scale formation and pre-treatment aspects of feed water are also discussed. Techno-economic viability of the MEWD system was also studied to see the feasibility of supplying drinking water to small rural communities.

Keywords: Vertical tube evaporator, Distillate, multi effect distillation.

1. INTRODUCTION
Drinking water standards are available to ascertain the fitness of water for human consumption. Water with total dissolved solids (TDS) content below 600 parts per million (ppm) has good palatability. Water with TDS above 1200 ppm is generally unacceptable to many, although acceptability may vary according to local circumstances (WHO, 2003) [1]. Generally for the purpose of drinking, TDS below 500 ppm is recommended by (BIS 1991) [2].The impurities in drinking water are of two classes. First is of chemical origin, due to dissolved salts. This could cause high TDS. Also, presence of certain dissolved salts containing toxicants such as arsenic etc., even at very low ppm levels, render the water hazardous for drinking. The high TDS is usually due to large amounts of sodium chloride, calcium and magnesium salts. In hard water Ca and Mg salts may be above 100 ppm levels. Also, the acceptable standards for some of the toxic chemicals such as As (0.005 ppm) and Hg (0.001ppm), are very low. Good reviews are given by Porteous (1975) [3], Shah et al. (1997) [4], Rheinlander and Grater (2001) [5] and Semiat (2000) [6].

The second reason for impotability is of biological origin, i.e. due to the presence of microbes such as bacteria and viruses. These kinds of impurities can be eliminated, either by boiling, or, in large plants, by flocculation, filtration and chlorination. These processes for removing biological contaminants do not make any noticeable change on the dissolved solids contents of the water. The challenge of water purification therefore is to lower the TDS to acceptable levels and to get rid of all toxicants present at very low ppm levels. Two systems of treatment have been developed over the years. The first is membrane based, such as Reverse Osmosis, and, the second is based on phase change, mainly distillation. The RO process has great merit in reducing TDS. However its effectiveness in removing low ppm chemical toxicants like arsenic etc. has to be carefully tested with the membrane operation characteristics. Also the greater the percentage of TDS to be removed the more is the reject water stream. One of the available options for distillation is solar distillation. This is effective but the amount of produced water per square meter of surface area capturing solar energy, is very small. Hence the plant has to be very large in physical size to get adequate product water. Amongst the other options are Multistage Flash (MSF), and Multiple Effect Distillation (MED). The advantage of MED is that the number of stages in MED systems is low in comparison to MSF systems. Use of large scale multiple effect distillation units (MED) for providing potable water is already in practice in Middle East and elsewhere. The challenge is however to design small scale units which could be operated locally in the rural sector, and this is the objective of the present work.

2. DESIGN AND OPERAION OF THE SMALL SCALE MEWD SYSTEM DEVELOPED

The schematic of the small scale MEWD system developed herein is shown in figures 1(a) and 1(b). Typically a triple effect system is shown which can be extended to six or more effects by increasing the number of evaporator modules. The design and fabrication of a MED system was made on the basis of equation of heat transfer as $m\, h_{fg} = U\, a\, \Delta T$

Considering steam rate from boiler (m) = 17 kg/hr,

Latent heat of vaporization h_{fg} = 2250 kJ/kg,

Overall heat transfer coefficient = 5000 W/m^{2o}C and Temperature difference between steam and hot feed water ΔT = 8^{o}C

Surface area a was determined as 0.3 m^2

To achieve this area seven number of aluminium tubes, as available in the market having diameter as 0.018 m and length as 0.75 m were chosen.

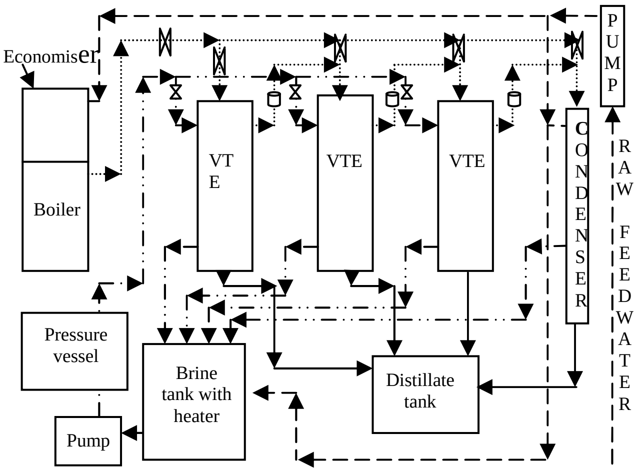

Fig 1(a): Schematic Triple-Effect MEWD Unit for parallel feed arrangement of feed water

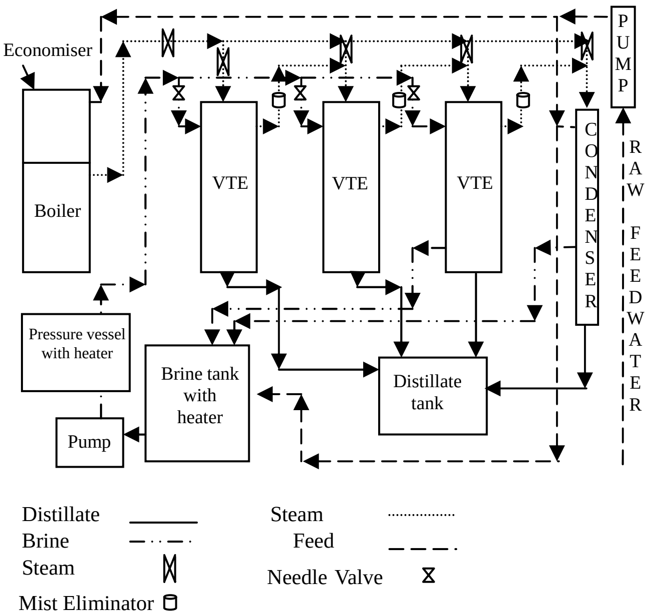

Fig 1(b): Schematic Triple-Effect MEWD Unit for forward and mix feed arrangement of feed water

The components of the system are:

(1) Baby boiler
(2) Vertical tube evaporators (VTEs)
(3) Condenser
(4)Mist eliminators or feed entrainment separators
(5) Distillate and brine withdrawal system
(6) Feed water preheaters
(7) Pump
(8) Other peripherals

Primary steam from the baby boiler enters the tube-side of VTE in the first effect and condenses there. The preheated feed water is fed into the shell side of VTE and the shell side is maintained at a lower pressure than the tube side. Thus the temperature in the shell side is lower than that in the tube side. Hence transfer of latent heat takes place from tube to shell side, and, steam condenses and comes out as produced distillate. Also part of the feed water on the shell side evaporates. The remaining water is called reject brine. Details are given in Sen et al. (2002, 2004) [7], [8].

In parallel feed arrangement the reject brine is taken out and passed on to the brine tank as shown in figure 1(a).

In forward feed arrangement the reject brine is passed on as feed water to the next stage. In mixed feed some additional feed water is also supplied from the parallel feed line as shown in figure 1 (b).

The fresh steam formed in any effect is passed through an inter-effect mist separator before being fed to the next effect, and the process repeated. The steam generated in the last effect is condensed in a falling-film condenser. This liquid-film is actually the feed water (to be decontaminated) which is preheated in this process. The distillate and brine are withdrawn using orifices, with millimeter sized holes. The brine from each of the effects, and preheated feed water from the condenser, is mixed in a brine tank and further heated to about 80-90°C before being pumped to a pressure vessel with heating arrangement. The brine mix is then fed into the shell side of VTEs. Thus, brine is recycled, and ultimately rejected at a predetermined concentration level. The distillate is collected in a distillation tank.

A fire tube baby boiler, capable of producing about 30 kg/hour steam, was selected. The boiler was fired using liquid petroleum gas (LPG) or by diesel for pilot scale studies. However, a biomass-fired boiler could be used for rural applications. The primary steam from the boiler is passed to the tube side of the first effect through a pressure-regulating valve (PRV) at nearly constant desired input steam pressure.

Evaporators constitute the heart of the system. Since flows involved are very small, of the range of 20-50 kg/h, use of VTE was preferred amongst various other designs considered. The VTEs are shell and tube heat exchangers. Readily available outside-fluted aluminium tubes, commonly used as curtain rods, are used in construction. These gave a very good overall heat transfer coefficient (OHTC). Some collateral heat transfer aspects may be seen in [9] Jin et al. (2002) and [10] Uche et al (2002). The construction details of a VTE are shown schematically in figure 2.

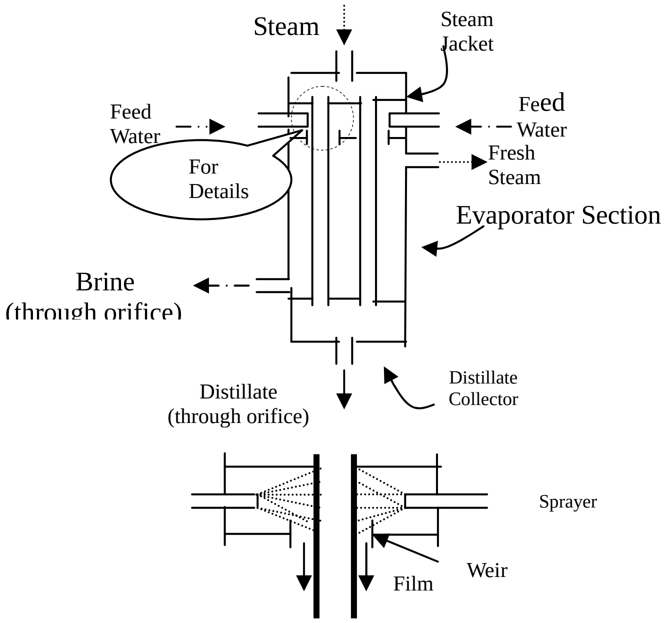

Fig 2: Schematic Vertical Tube Evaporator

The shell is divided into four parts; namely, steam jacket, feedwater jacket, evaporator section, and distillate collector. The feedwater is sprayed over the tubes by means of two sprayers. For uniform feedwater distribution to all the tubes, a weir arrangement is also made use of.

To overcome the problem of brine being carried along with the fresh steam formed, and thus polluting the distillate, inter-effect mist separators were designed. These are made of 0.3 m long MS pipe with 0.1 m diameter. The fresh steam (laden with mist) from the shell side of the VTEs enters and strikes the central part of the pipe longitudinally. The mist gets separated due to cyclonic effect as the steam strikes the pipe wall and the mist is collected at the bottom and steam exits from the top of the separator. The steam therefore enters into the tube side of the next effect and the process continues. Distillate and brine are withdrawn using small size orifices. The system remains positively vented; thus, the non-condensable gases (NCG) or entrained air also gets flushed out through these orifices. The brine is removed using 2-3 mm orifices and distillate is taken out using 1-1.5 mm orifices.

The distillate and brine are withdrawn from each effect at a fast-enough rate so that no flooding occurs. On the tube-side of the VTE, some steam is lost through the distillate withdrawal orifice after all the distillate is drawn out. Similarly, some steam is lost through the orifice on the shell-side of VTE for discharging brine. Thus, both liquid and steam are discharged through the two orifices. The orifice sizes are so chosen, that, it is (more than) sufficient to withdraw all the liquid at the given pressure differential. This ensures that no flooding occurs on tube or shell side of the VTEs. Orifice sizes larger than that just required will result in a little steam loss through the orifice. However, the steam choking velocities at a higher pressure and the low density of steam restrict excessive steam loss. With proper choice of the orifice size, steam loss can be kept to within 5 percent. Thus, selecting an appropriate size orifice is of paramount importance. If an orifice is designed to discharge a maximum flow of liquid q_{lm}, and actual rate of flow of liquid withdrawal is q_l, then the time fraction for liquid withdrawal will be q_l / q_{lm} , with $q_l < q_{lm}$.

3. EXPERIMENTATION AND ANALYSIS

The parameters such as temperature, pressure, brine rate, distillate rate, etc. were measured. The primary input steam to the system as well as the vapours passed to the subsequent effects, are dry saturated; and the steam loss through orifices constitutes the major source of heat and mass loss from the system, besides the little heat that is lost to surroundings. Neglecting steam loss through orifices q_f is calculated using eq. (1) Value of overall heat transfer coefficient U is calculated using eq. (2), where ΔT and a are respectively, the temperature difference across tube and shell sides and the heat transfer surface area of tubes in VTE:

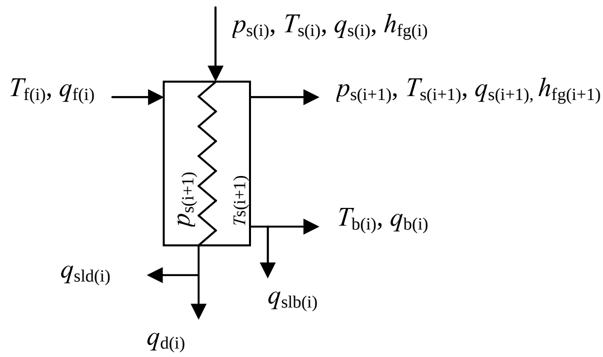

Fig 3: Schematic Representation of Variables in a Typical Effect (i)

$$q_{f(i)} = q_{b(i)} + q_{d(i+1)} \quad (1)$$

$$q_{d\,(i)}\, h_{fg\,(i)} = U_{(i)}\, a_{(i)}\, \Delta T_{(i)} \quad (2)$$

q_f = input feed water rate

q_b = withdrawn brine flow rate

q_d = rate of condensate

h_{fg} = latent heat of vaporization of steam

U_i = heat transfer coefficient

a_i = area of heat transfer surface

ΔT_i = temperature difference

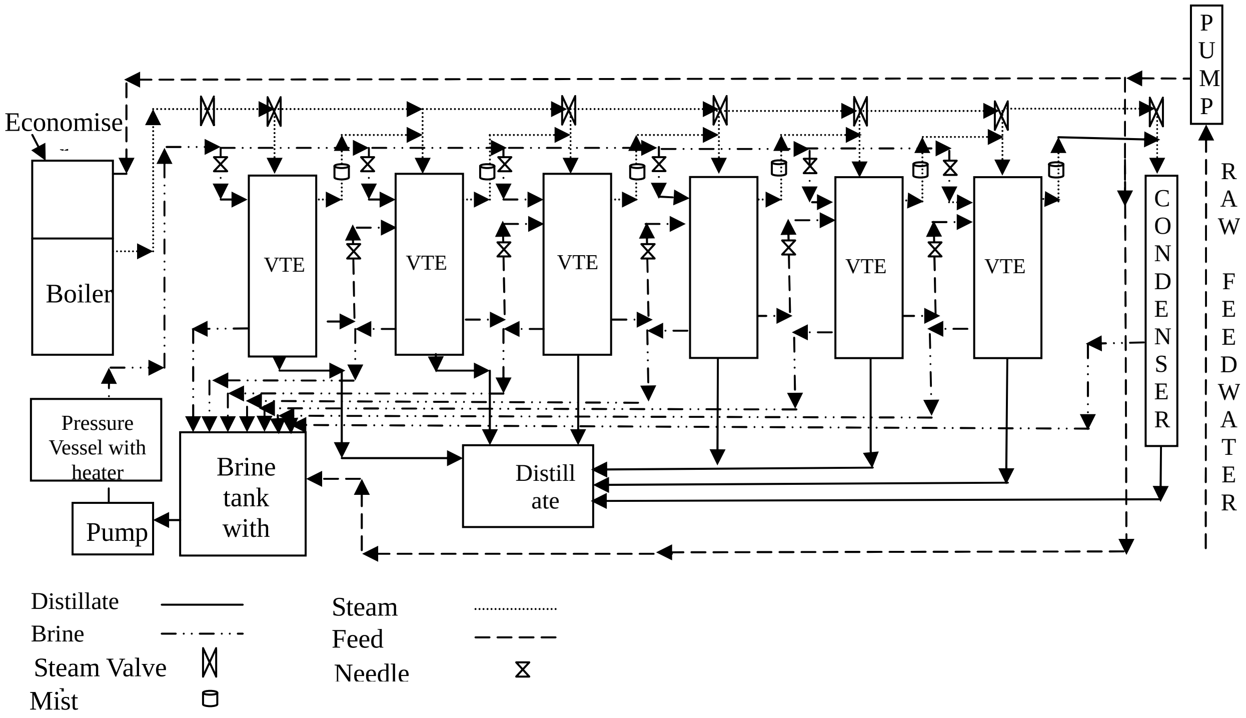

Fig 4: Schematic representation of the six-effect MEWD system

3. DESIGN AND FABRICATION OF SIX EFFECT MEWD SYSTEM

The six effect unit is shown in figure no. 4. In this six effect unit arrangements have been made to feed the brine in the following configurations so that comparison can be made by running the system in selected modes such as:

(1) Parallel feed;

(2) Forward feed;

(3) Mixed feed.

In parallel feed arrangement, the feed water enters each effect from the same feed brine pipe and all the brine that comes out from each effect is collected in a common tank. After addition of makeup feed water, the mixture in the tank is heated to a desired temperature and then pumped to each effect in parallel through a common feed line.

For experimental purposes, the forward feed arrangement can be selected besides the parallel feed arrangement so that option for mixed feed is also available. In the present arrangement part of the brine is fed in forward feed mode and part of the brine is fed in parallel mode.

In the forward feed mode, valves have been introduced in connecting effects to separate different feed lines. In this way it is possible to experiment with any feed mode at a time. The feed water configuration and schematic diagram of the manufactured unit is shown in fig. 4.

Different feed water configurations have been tried and it was observed that an input primary pressure of almost 4 kg/cm^2 is required to operate six effects wherein brine from one effect to the other would move on its own. i.e., the brine coming out from one unit reaches the next effect under the pressure of steam itself.

Replacing parallel feed by forward feed configuration would lead to the following:

(1) Better use of heat of brine is possible

(2) Brine received from one effect is sent to next effect directly by the pressure of steam itself.

(3) The changed configuration completely eliminates steam flashing at the time of brine withdrawal.

4. PLANT PERFORMANCE FOR SIX EFFECT SYSTEM

The plant was run under the selected conditions and total distillate of about 100 kg/h was produced using six effects for the following set of input parameters:

Primary steam input temperature: 144°C

Primary steam input rate: 20.5 kg/hr

Feedwater flow rate to each effect: 50 kg/hr
(For parallel feed configuration)

Feedwater flow rate to first effect: 110 kg/hr

(For forward feed configuration)

Feedwater input temperature to each effect: 90°C

OHTC for each effect: 5000 W/m^2°C

Atmospheric pressure and temperature: 742.5 mm Hg, 35°C

The experimental values (measured) of temperature, pressure and condensate are compared with values calculated using the simulation model developed based on basic heat and mass balance. The results are shown in fig. 5. The gained output ratio (GOR)* of the plant decreased with increase in number of effects for parallel feed configuration. The GOR value for the triple effect unit is 2.84. For the six-effect system, GOR is reduced to 2.37 for a parallel feedwater configuration mainly due to the external energy needed in preheating feedwater which has become more than double the primary steam input. However, GOR for the six- effect system using forward feed comes out 3.07 which is significantly larger than that for parallel feed configurations. GOR for mixed feed configuration is 3.02 which is slightly less than that for forward feed configuration. Thus, the overall steam economy is found optimal on using forward feed configuration.

* GOR: It is the ratio of distillate produced to the total input energy in terms of steam

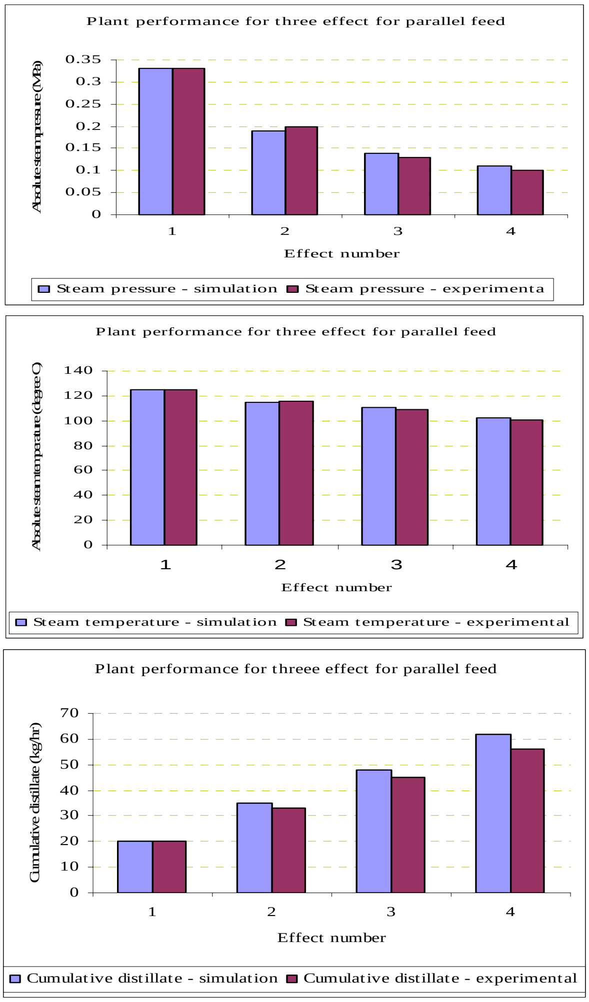

Fig 5(a): Plant performance for triple effect system with

5. TECHNO-ECONOMIC FEASIBILITY FOR RURAL AREAS

The cost analysis has taken into consideration the daily fixed cost and daily operating costs. Daily fixed cost was worked out considering annuity, maintenance cost, and number of working days. The different costing units for the fixed cost included the cost of boiler, evaporators and peripherals, and maintenance cost etc. The daily operating cost includes the labour and fuel charges. Different fuels such as LPG, charcoal, briquette, firewood and biomass were considered as the source of energy. The cost of raising primary steam was found to be the least using biomass. The energy cost per unit distillate produced for different number of effects was analyzed using various cost parameters such as the primary steam raising cost, the energy cost in preheating feedwater, the pumping cost etc. For the same fuel, the energy cost per unit distillate in preheating feedwater increased with increase in number of effects. However, the total cost per unit distillate (excluding labour charges for the daily operation) reduced with the increase in number of effects. However, this decrease was not in the same proportion as the increase in number of effects. This is shown in figure 6. In this figure, total daily cost includes daily fixed charges and daily fuel charges in running boiler, pump and preheating feedwater. The daily preheating energy requirement increased

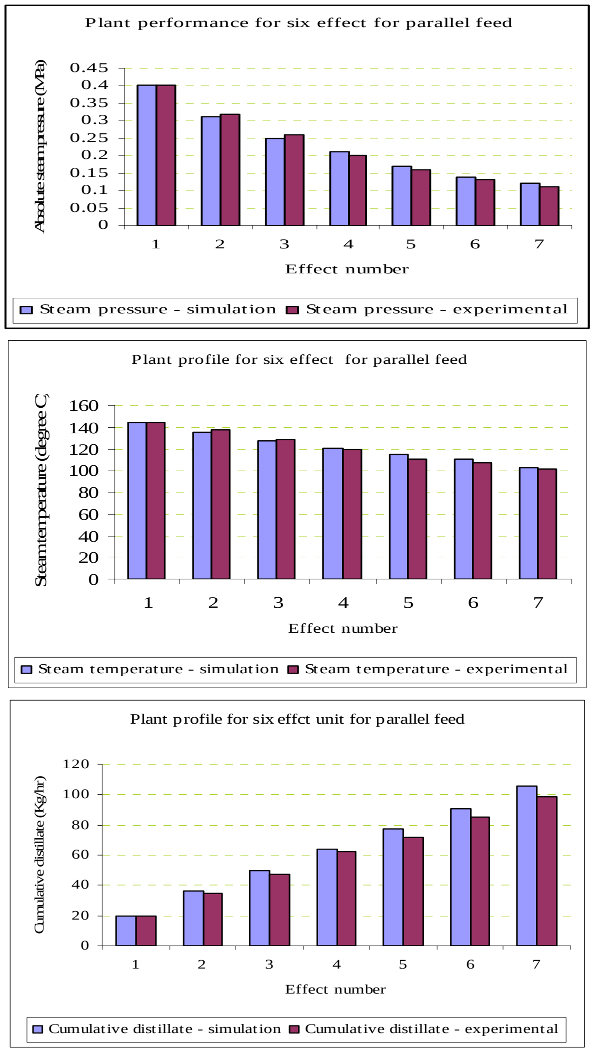

Fig 5(b): Plant performance for six-effect system for parallel feed with condenser

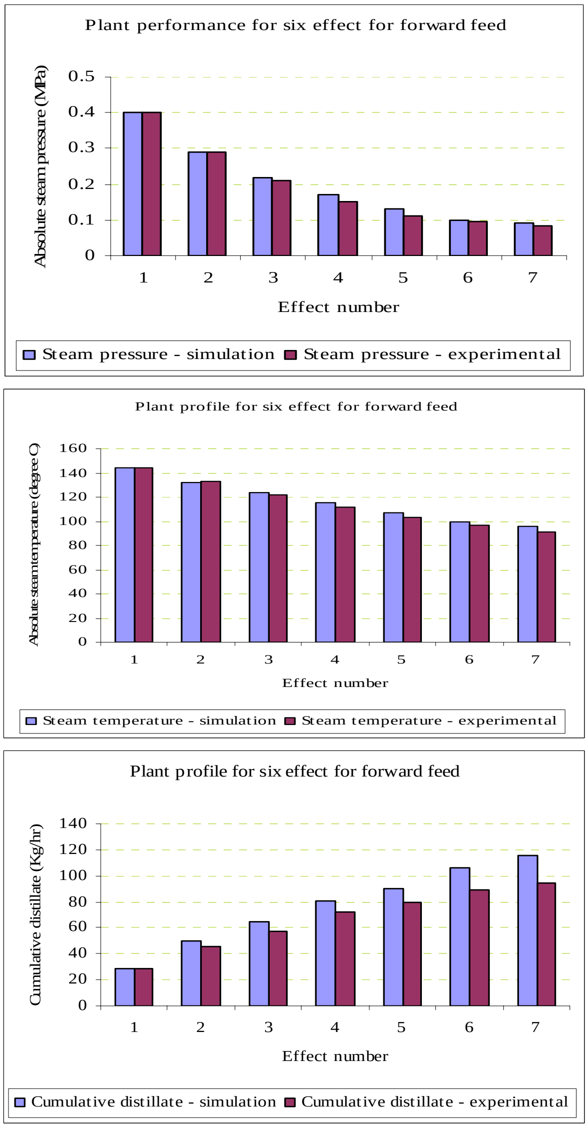

Fig 5(c): Plant performance for six-effect system for forward feed with condenser

substantially with increase in number of effects. However, this can be reduced by preheating of feedwater using waste steam through orifices and flashed steam produced from distillate. The direct feeding of brine from a previous effect, say (i)th effect to (i+1)th or (i+2)th effect, has been considered in this study. This would reduce preheating feedwater requirements.

Distillate cost for six effects using forward feed configuration is found minimum i.e. Rs. 0.17 per kg of distillate produced, if biomass is used for steam formation and feedwater preheating. If LPG is used for the same purpose the cost per kg of distillate produced comes out as Rs. 0.41.

In the rural scenario, the daily labour can come from the community on co-operative basis. The user families can also supply biomass, thus reducing the cost. In case the plant is to be run on a commercial basis, the labour cost may be added for one person in each shift of 8 hours. It is seen that the distilled water can be produced at less than Rs.0.25 per litre on a commercial basis. This includes the remineralisation cost of distilled water, which is very small about Rs. 0.01 per litre.

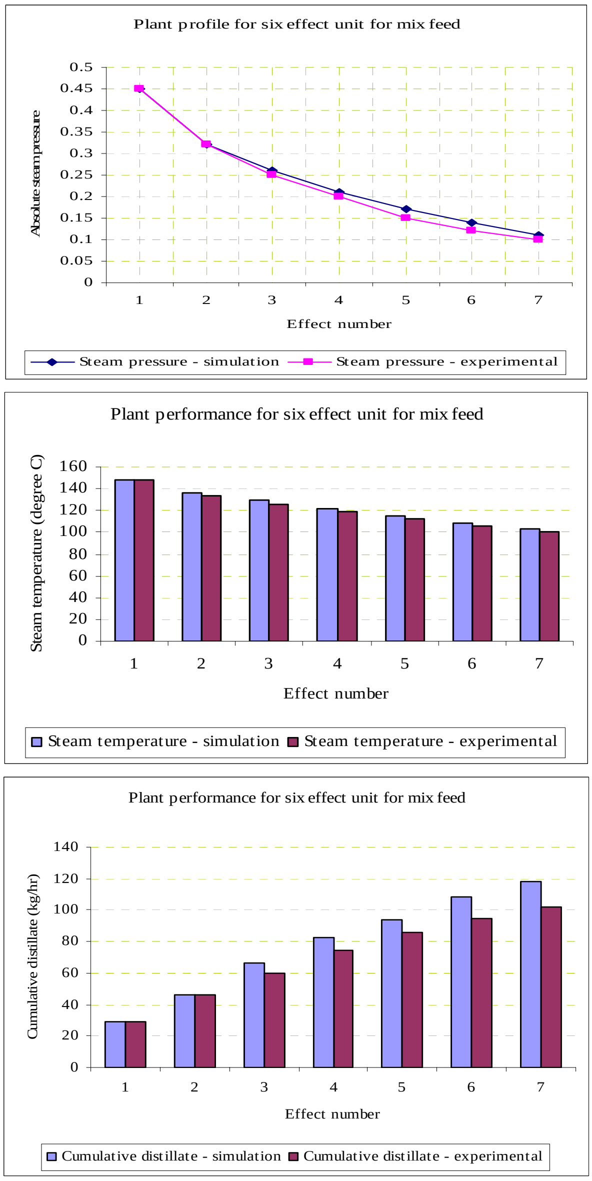

Fig 5(d): Plant performance for six-effect system for mix feed with condenser

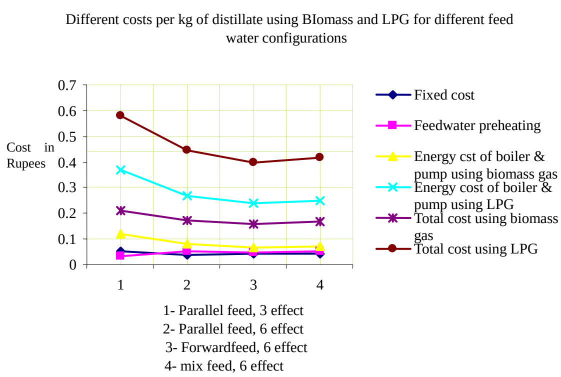

Fig 6: Variation in different cost components and total cost per unit distillate with number of effects

The water can be sold as drinking water and also for other uses such as battery water and base water for making beverages etc.

6. CONCLUSION

From the detailed analysis of results obtained for different modifications and feed water configurations we can conclude that steam efficiency or GOR is maximum for forward feed mode. Cost of distillate also the minimum for the same feed water mode. The following specific conclusions emerge-

(1) Water distillation unit using multiple effects have been constructed using local materials and simple technology.

(2) The unit manufactured is rugged and can be easily operated, repaired and maintained by a village mechanic.

(3) The unit works at supra-atmospheric pressure.

(4) Steam loss through brine withdrawal has been eliminated by replacing brine orifice with inter effect valves.

(5) The distillate is withdrawn using orifices without allowing appreciable steam loss.

(6) Positive displacement pump is being used to feed the brine. It can handle high process temperature etc.

(7) Forward feed arrangement leads to better efficiency and the load on pump to feed brine to the next effect is reduced. This saves power or money.

(8) Distilled water is produced at a cost affordable by rural population.

7. ACKNOWLEDGEMENTS

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