Experimental investigation of maldistribution in vertical plate falling film tower

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Abstract

Falling film towers are popular in process industries due to moderate air side pressure drop, less energy ingesting liquid distribution and easy cleanup features. Two major limitations of falling film towers are the uneven distribution of liquid across solid surfaces (maldistribution) and contraction of falling liquid film on the solid surface (poor wetting). Maldistribution of liquid is primarily dependent on the type of liquid distributor and scope of liquid flow (slit opening) across solid surfaces. In the current communication; the influence of liquid distributor on maldistribution problem of vertical plate falling film tower has been experimentally investigated. Four types of liquid distributors: plain tube, spray nozzle, perforated plate, and branch tube distributor have been tested. Effect of parameters: slit opening, liquid flow rate and the number of plates on maldistribution are also explored. It is found that branch tube distributor is best suited for vertical plate falling film tower application.

Keywords:falling film tower, maldistribution, liquid distributor, spray nozzle.

1. Introduction

Simultaneous heat and mass transfer operation is the soul of many process industries such as based on distillation, adsorption, absorption, precipitation, drying, etc. In fact, the heat transfer phenomenon is an integral part of mass transfer operations. Packed bed, spray and falling film towers are three conventional design used for above purpose. Packed beds are the most popular and extensively used design due to very high contact area per unit volume and high mass transfer coefficient. The main limitations of this design are high air side pressure drop and high liquid flow requirements (Wang et al., 2016). Spray tower has the least air side pressure drop, but its main limitations are energy intensive liquid distribution and carryover problem (Kumar et al., 2011).

Falling film towers have moderate air side pressure drop and can operate efficiently at low mass flow rate with less energy ingesting distributor (Kumar et al., 2009). The most important feature of these towers is external heat transfer facility thus it is possible to minimize the side effect of integral heat (associated with mass transfer) on overall mass transfer operation. They are in high demands in the milk and juice process industries due to easy cleanup and long life of the tower (Coustel and Journet, 2009). Liquid drops under the influence of gravity in the form of continuous film across the solid surfaces in these towers. Two main limitations of falling film towers are: maldistribution of liquid across solid surfaces and limited wetness of solid surface due to contraction of the liquid film in the downward direction. The limited wetness of solid surface can be improved by the addition of suitable surfactants (Cheng et al., 2004; Kang et al., 2007) and surface modification techniques (Kim et al., 2003; Koroglu et al., 2013; Patil et al., 2016). Maldistribution of flow across solid surfaces is very much dependent on the type of liquid distributor and scope of flow across solid surfaces.

The problem of liquid maldistribution and its adverse impact on the performance of the mass transfer reactors had been identified long back. Baker et al. (1935) experimentally studied liquid flow distribution in packed bed column with broken stones, spheres and saddles as packings. They found significant effect of packing size to column size ratio on liquid maldistribution. Scott (1935) also studied liquid distribution in packed bed columns and attributed the tendency of the liquid to spread towards column wall as the main reason for distortion of flow with increase in packing height. Porter et al. (1968) experimentally verified the effect of maldistribution by measuring flow across small sampling areas at the bottom of randomly packed (ceramic Raschig rings) tower and found that liquid flows in the form of small and large rivulets. Hoek (1983) measured and compared the maldistribution effect in stacked packed and dumped packed column.

He observed very less maldistribution in stacked packed column and large maldistribution in dumped packed column. Fitz et al. (1999) studied the separation performance (cyclohexane/*n*-heptane system) of structured packing using adjustable liquid distributor (drip point variation from 12 to 103 drip points/m^2). They found that structured packing was more sensitive to maldistribution than random packing. Yin et al. (2000) carried experimental study on a randomly packed column. They found that liquid distributor design, packed bed height, gas flow rate and liquid viscosity strongly influenced the liquid distribution, whereas liquid flow rate slightly influenced the liquid distribution. Olujic et al. (2006) experimentally compared the liquid distribution behavior of two structured packings (Montz Pak B1 and high capacity Montz Pak B1-250M) using trough distributor. They found maldistribution of 22% and 15% for conventional and high capacity packing. Spigel (2006) compared the wetted index (ratio of wetted to total cross-section area) of drip point distributor (160 drip points/m^2) and baffle plate distributor of Sulzer (5 drip lines/m). He found that baffle plate distributor was around 23% efficient than drip point arrangement for the same liquid loading conditions. Alix and Raynal (2008) experimentally compared the maldistribution effect of modern high capacity structured (MellapakPlus 252 Y) and random (IMPT 50) packings using drip point distributor (347 drip points/m^2). Liquid maldistribution parameter of around ± 10 and ± 20% was found for structured and random packing respectively. Llamas et al. (2008) developed wire mesh tomography sensors to measure the liquid maldistribution in trickle bed reactor. They concluded that wire mesh tomography method is good for visualization of liquid distribution due to its simplicity and low cost. Xu et al. (2009) experimentally compared the effect of nozzle distributor and packed bed distributor (bed of 1 mm glass bead packing) on flow distribution in a multiphase monolith packed reactor. They found that packed bed distributor had better liquid and gas distribution capability compared to nozzle distributor, but it was associated with larger pressure drop. Fourati et al. (2012) studied liquid dispersion on structured packed bed column (Mellapak 250 X) using central liquid jet distributor by gamma ray tomography method. They observed that liquid spread did not vary significantly in the flooding range of 20–80%.

It is clear that most of the previous research studies related with maldistribution had been carried out on packed bed towers. However, almost no effort has been made to study the maldistribution problem in falling film tower. Hence in the current study, an attempt has been made to understand, how the maldistribution problem behaves in case of vertical plate falling film tower (using four different types of liquid distributors: plain tube, spray nozzle, perforated plate and branch tube distributor).

2. Experimental Test rig and Experimentation

Multi-plate vertical falling film tower setup is fabricated for the study of maldistribution problem. Hollow square cross-section of size (L x B) (270 x 270) made from 8 mm thick transparent acrylic sheet of height 600 mm is used as a vertical tower. The vertical tower can accommodate total six number of plates (N) polypropylene (PP) plates of size (t x L x H) (10 x 100 x 600) placed at an equal distance of 30 mm from each other. The setup also consists of a liquid distributor, liquid supply and return lines, supply tank (200 litres PP tank), discharge tank (60litres PP tank), liquid separating channels and collection buckets. Liquid distributor header is hollow square (L x B) (270 x 270) cylinder of height 200 mm made from PP plate of 10 mm thickness. The bottom plate of the distributor header is made on CNC machine such that it facilitates tight press fit holding of six vertical PP plates and also provides a uniform scope of flow (slit opening) across each solid plate; as shown in Fig. 1 (a). Three such bottom plates with slit opening of 1, 1.5 and 2 mm are prepared to analyze an effect of the slit opening on maldistribution, Fig. 1 (b) shows details of the bottom plate with slit opening of 1 mm. Fig. 2 (a) shows the schematic diagram of experimental setup. Liquid separating channel is attached by nails at the end of each plate; these channels are held together at both ends by the side strips as shown in Fig. 2 (b). Liquid separating channels arrangement ensures separate collection of liquid falling through each plate. The lower end of liquid separating channels is connected through a flexible pipe to either discharge tank/collection buckets (22 litres).

Tap water is used as the working fluid in the current study. Unlike the packed bed tower, the effect of gas flow rate on maldistribution is almost negligible for the falling film tower. Hence, no provision for air flow is kept in the current study. With the help of monoblock pump (Kirloskar chotu, 0.5 hp) liquid is supplied to the inlet of distributor box. Liquid flow rate in the supply line is controlled by two ball valves and quantified with the help of a rotameter (1.5–15 litre per minute (LPM)). Liquid falls on both sides of each plate and collects in the used tank; liquid collected in the used tank is passed back to the supply tank through submerged pump. For measuring the flow rate through each plate, the liquid is collected in the collection buckets of each plate for the duration of 120 seconds. Before the start of an experiment, water is well stirred inside the supply tank for 3 min. For avoiding the effect of any initial instability, system is initially run for ten min before starting measurement of flow across solid plates. Maldistribution factor (M.F.) has been calculated following Eq. (1) in the current study.

$$M.F. = (\dot{m}_i - \dot{m}_{avg})/\dot{m}_{avg}$$

Where $\dot{m}_{avg} = \sum \dot{m}_i/N$

Four types of liquid distributors are used in the current study to investigate the effect of distributor design on maldistribution problem in falling film tower; they are shown in Fig. 3. The first one (Fig. 3 (a)) is the plain tube distributor (d = 12.5 mm). As the recesses around each plate were small (1-2 mm) so the idea was that even pipe distributor will facilitate proper distribution. The second one (Fig. 3 (b)) is the spray nozzle distributor (Spraying Systems Co., QPHA-10). The third one (Fig. 3 (c)) is the perforated plate distributor, formed by drilling series of circular holes of diameters (3 mm, 4 mm and 5 mm) on PP plate of rectangular footprint area ((W, B) (110, 230)). The holes of 3 mm diameter are drilled in the center portion of perforated plate followed by holes of 4 mm and 5 mm diameter towards the edges respectively to avoid the problem of more flow in central plates. The fourth one (Fig. 3 (d)) is the branch tube distributor; it consists of header pipe (d = 12.5 mm) having branches of six tubes of diameter 5 mm and length 3 cm placed at equidistance of 40 mm. The branch tube diameter is chosen such that the summation of a cross-sectional area of six openings is equal to the inner cross section area of the header tube for avoiding maldistribution. The reference conditions for the current experiments are given in table 1.

3. Results and Discussion

3.1. Effect of location of the plate on maldistribution

Figure 4, 6, 8 and 9 show that maldistribution of the plate depends on its distance from the distributor. In general, those plates (plate no. 3 and 4) which are closer to the distributor; they are supplied with maximum fluid in spite of keeping the same slit opening. In the current study, these plates are supplied liquid around 1.5 times more than the average ideal condition (except for the branch tube distributor). Liquid flow in the subsequent plates (plate no. 2 and 5) decreases as the distance from the distributor increases. Interesting behavior has been observed for the last plates (plate no. 1 and 6), their maldistribution is lesser than the previous plates (plate no. 2 and 5). The above can be credited to the side wall effect because of which excess liquid strikes back in opposite direction after hitting the side walls and finally flow through the last plates. It is clear that problem of maldistribution adversely influences the flow rates of liquid in parallel plates of vertical falling film tower, which would certainly have the severe impact on the performance of falling film tower. It is also observed that liquid flow rate through spray nozzle is almost half, if the inlet and return line openings are kept same, which may be due to a high-pressure drop in case of the spray nozzle.

3.2. Effect of the slit opening on maldistribution

Fig. 4 (a-d) shows the effect of the slit opening on liquid maldistribution for all the four distributors. It can be observed that the effect of the slit opening on maldistribution is almost negligible (slight increase in positive maldistribution of the plate no. 3 and 4) for the plain tube distributor. The above behavior can be attributed to the high momentum of thick water slug as it hits the base of distributor and spreads quickly in case of the plain tube. However for spray nozzle and perforated plate distributor, the positive maldistribution increases significantly around 120% for spray nozzle and 18% for the perforated plate in case slit opening is more than 1 mm. The above can be attributed to the excess flow tendency of these distributors corresponding to central locations. Thus with the increase in slit opening; more liquid starts flowing through the central plates (plate no. 3 and 4) and their positive maldistribution increases. However, no regular patterns have been observed for rest of plates, but average absolute M.F. for both distributors (spray nozzle and perforated plate) increases for slit opening of more than 1 mm. Less maldistribution for spray nozzle is due to the generation of uniform & fine liquid droplets by it, which facilitates uniform distribution of the liquid across each plate. Maldistribution factor reduces significantly for branch tube distributor, but maximum and average absolute maldistribution for branch tube distributor also increases slightly for slit opening of more than 1 mm. Experiments are repeated for high flow rates (9 and 12 LPM) even by varying the slit opening (1, 1.5 and 2 mm). But, it is found that at high flow rates, if slit opening is more than 1 mm then liquid spills without wetting the solid surface (Fig. 5). Thus, slit opening of 1 mm seems to be optimized considering maldistribution effect and therefore, rest of the experiments are carried out with slit opening of 1 mm.

3.3. Effect of the flow rate on maldistribution

Fig. 6 (a-d) shows the effect of mass flow rate on maldistribution. It is found that maldistribution problem decreases with increase in flow rate except for branch tube distributor. With plain tube distributor, M.F. of plates closest to the center (plate no. 3 and 4) reduced from 1.4 to 0.5 when the liquid flow rate is increased from 6 LPM to 12 LPM. The starved condition of plates 3 & 4 arises due to increase in hydraulic jump (Fig. 7), which improves the distribution in rest of the plates. The above effect significantly influences the performance of spray nozzle and perforated plate distributor. For spray nozzle also maldistribution problem visibly reduces at high flow rates especially for side plates (plate no. 1 and 6). This may be due to the high velocity of fine liquid droplets at large flow rates, which induces liquid droplets to settle towards outer plates. For the branch tube distributor, central plates (plate no. 3 and 4) maldistribution slightly becomes positive and side plates maldistribution becomes slightly negative at high flow rates. But, the overall performance of branch tube distribution remains invariant to mass flow rate also.

3.4. Effect of the number of plates on maldistribution

Fig. 8 (a-d) shows the effect of a number of plates on maldistribution problem of falling film tower. For two plates, almost no maldistribution problem has been observed for plain pipe, spray nozzle and branch tube distributor but slight maldistribution problem has been noticed for perforated plate distributor. Above may be due to experimental uncertainty. For four plate case, maximum and average absolute maldistributions for the plain tube, spray nozzle, perforated plate and branch tube distributor are (0.65, 0.60), (0.41, 0.29), (0.91, 0.82) and (0.18, 0.10) respectively. Similarly for six plates case, maximum and average absolute maldistributions for the plain tube, spray nozzle, perforated plate and branch tube distributors are (1.45, 0.94), (0.83, 0.70), (1.63, 1.06) and (0.08, 0.05) respectively. It is clear that as the number of plates increases, the problem of maldistribution also increases. Out of the four distributors, the problem of maldistribution with increasing number of plates is the least for branch tube distributor.

3.5. Effect of the height of distributor on maldistribution

The effect of varying height of distributor on maldistribution problem is shown in Fig. 9 (a-d). It is clear that height of the liquid distributor is not having any significance influence on the maldistribution problem except for spray nozzle distributor. For the spray nozzle distributor, maldistribution pattern for 15 mm and 25 mm height are found to be same, but average maldistribution of plates 3 and 4 decrease by the factor of 0.30 when distributor height is increased to 35 mm. The above may be possibly due to increase in liquid spray cone base area, thus less intense central core distribution of liquid droplets occurs. Furthermore, similar experiments are carried at high flow rates also. It is found that height of the distributor is having the negligible effect on maldistribution problem.

4. Conclusion

In the current experimental study, the problem of maldistribution in multi-plate vertical falling film tower has been studied using four liquid distributors: plain tube, spray nozzle, perforated plate and branch tube distributor. The effect of different parameters location of the plate, slit opening, mass flow rate of liquid, the number of plates and height of the distributor on maldistribution have also been studied in the current work. The large variation in flow rates of liquid has been observed, plates closest to the central location (M.F. 1.45 for plate no 3 and 4) are found to be with positive maldistribution and towards the wall with negative maldistribution (M.F. -0.9 for plate no 2 and 5). It is found that slit opening of 1 mm is optimized condition considering the influence of maldistribution and high liquid spilling out of the surface problems. It is also found that problem of liquid maldistribution increases at low flow rate and in case the number of plates increases. However, the height of the distributor is not having any significant influence on the maldistribution problem except for the spray nozzle distributor. The maximum and average M.F. for these distributors are found to be as follow: plain tube (1.54, 0.77), spray nozzle (1.26, 0.62), perforated plate (1.98, 0.98) and branch tube distributor (0.24, 0.07). Thus, the performance of the branch tube distributor is found to be with least maldistribution problem and its performance is even found to be the most consistent among the four tested distributors.

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NOMENCLATURE

Notation

Symbols

A area (cm^2)

B breadth (mm)

d diameter (mm)

H height (mm)

L length (mm)

t thickness (mm)

$\dot{m}$ mass flow rate (kg/sec)

W width of plate (mm)

Sub- and Superscripts

avg average

i i^{th} plate

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Table 1 Reference conditions for current study

Parameter	Value	Unit

Flow rate	6	LPM
Slit opening	1	mm
Height of distributor opening	35	mm
Number of plates	6	

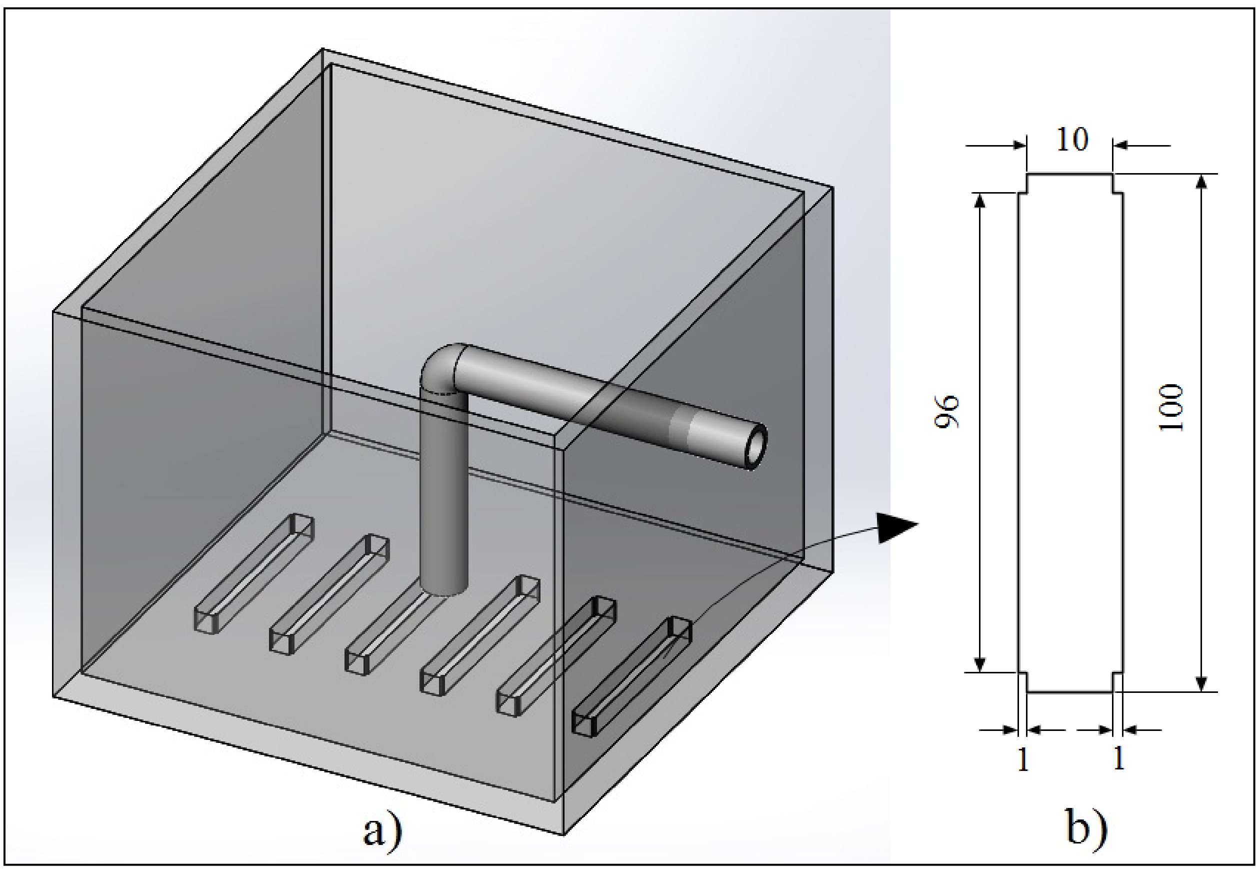

Fig. 1 (a) 3D view of (a) liquid distributor header (b) design of slit openings

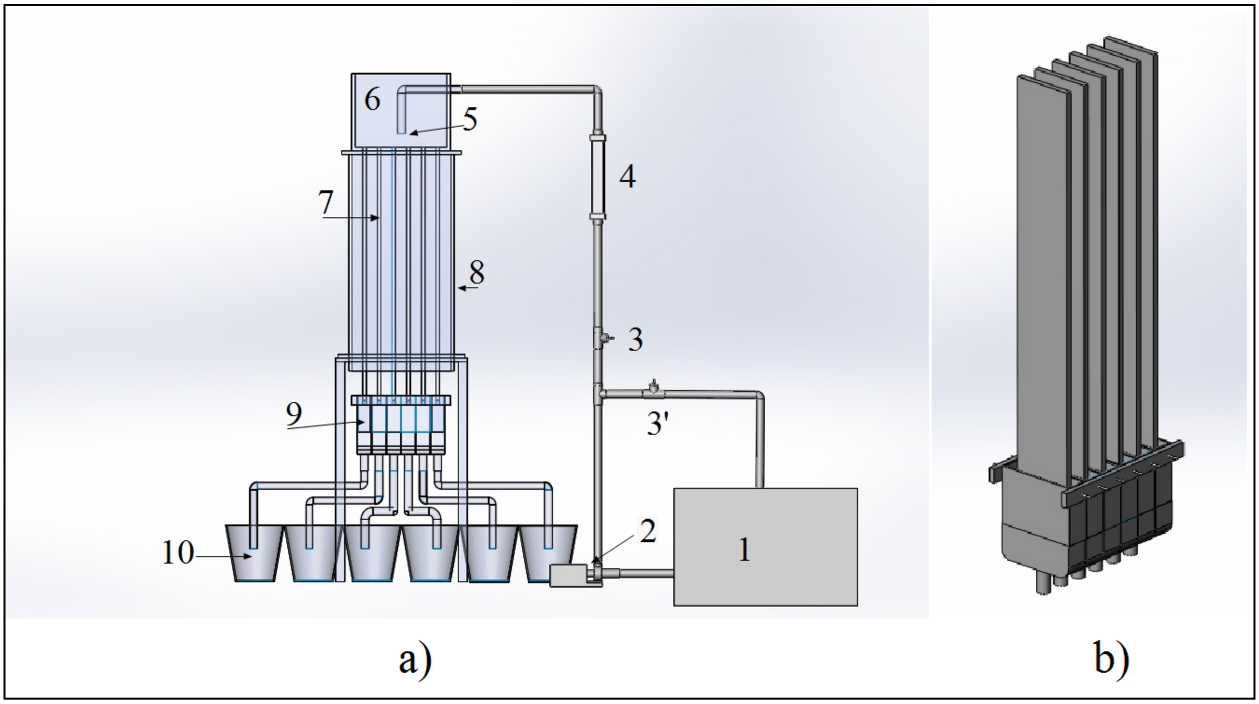

Fig. 2 (a) Schematic view of experimental setup (1-supply tank, 2-pump, 3 & 3'- ball valve, 4-rotameter, 5- liquid distributor, 6- distributor header, 7- vertical plates, 8- vertical tower, 9-collection bottle, 10- collection bucket) (b) 3D view of plates with water collection arrangement

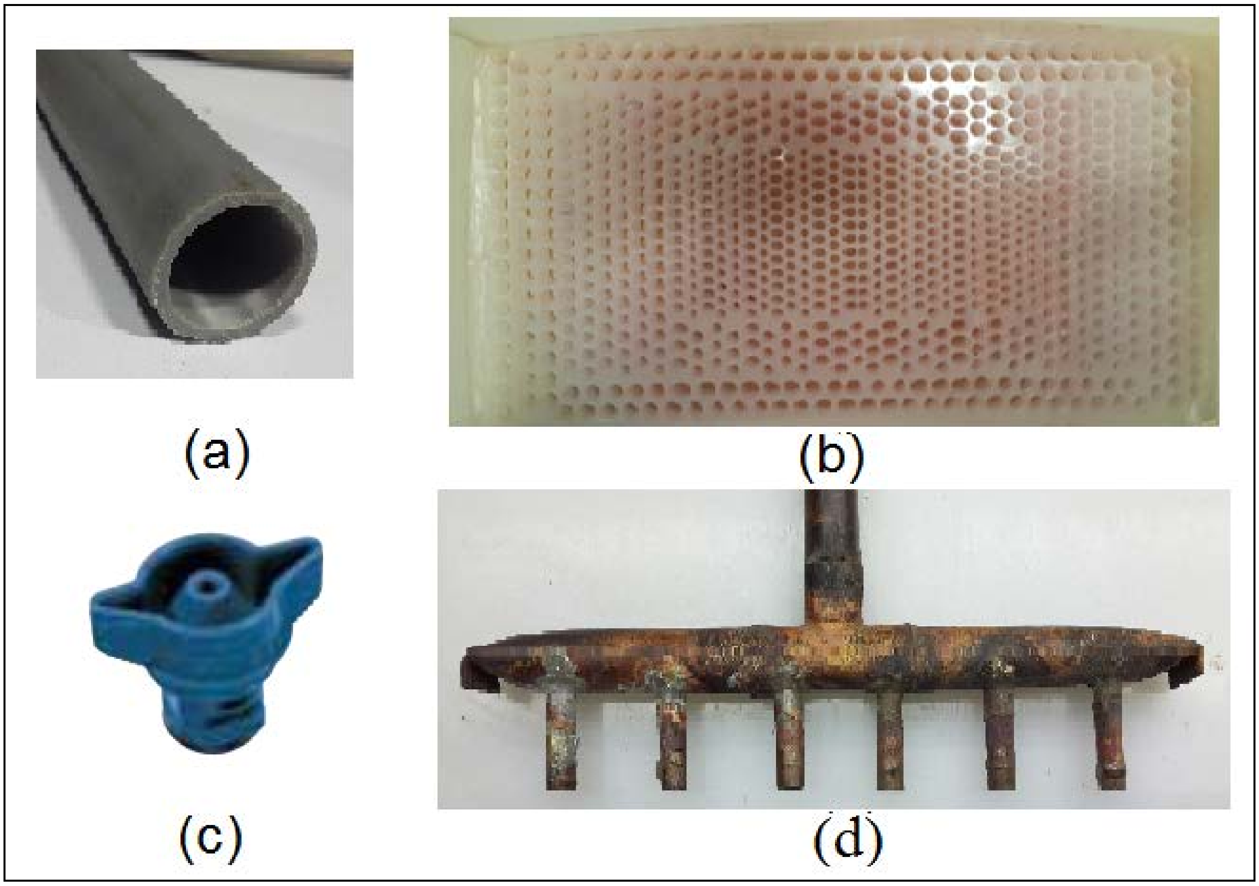

Fig. 3 Liquid distributors used: a) plain tube b) spray nozzle c) perforated plate d) branch tube distributor

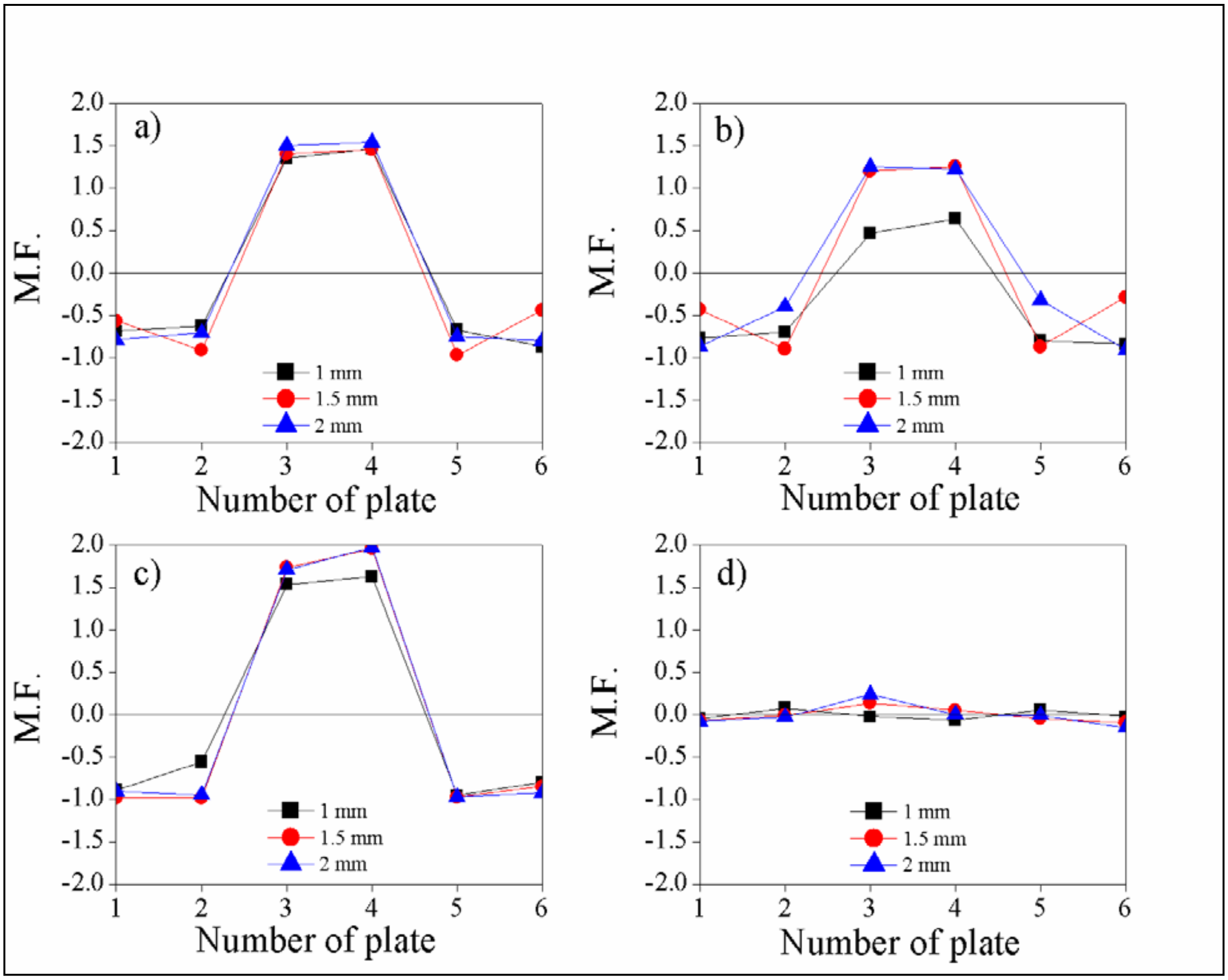

Fig. 4 Effect of the slit opening on maldistribution: a) plain tube b) spray nozzle c) perforated plate d) branch tube distributor

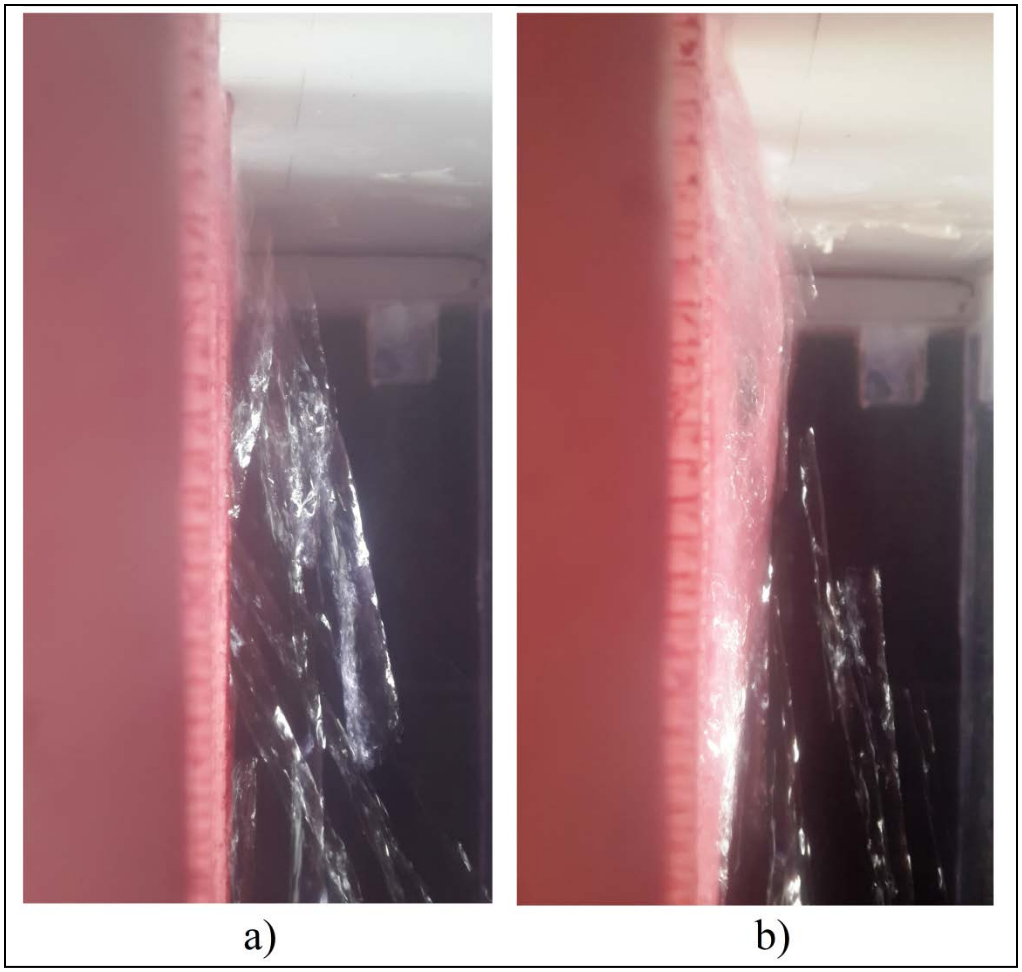

Fig. 5 Liquid film detachment from plate: a) 9 LPM b) 12 LPM

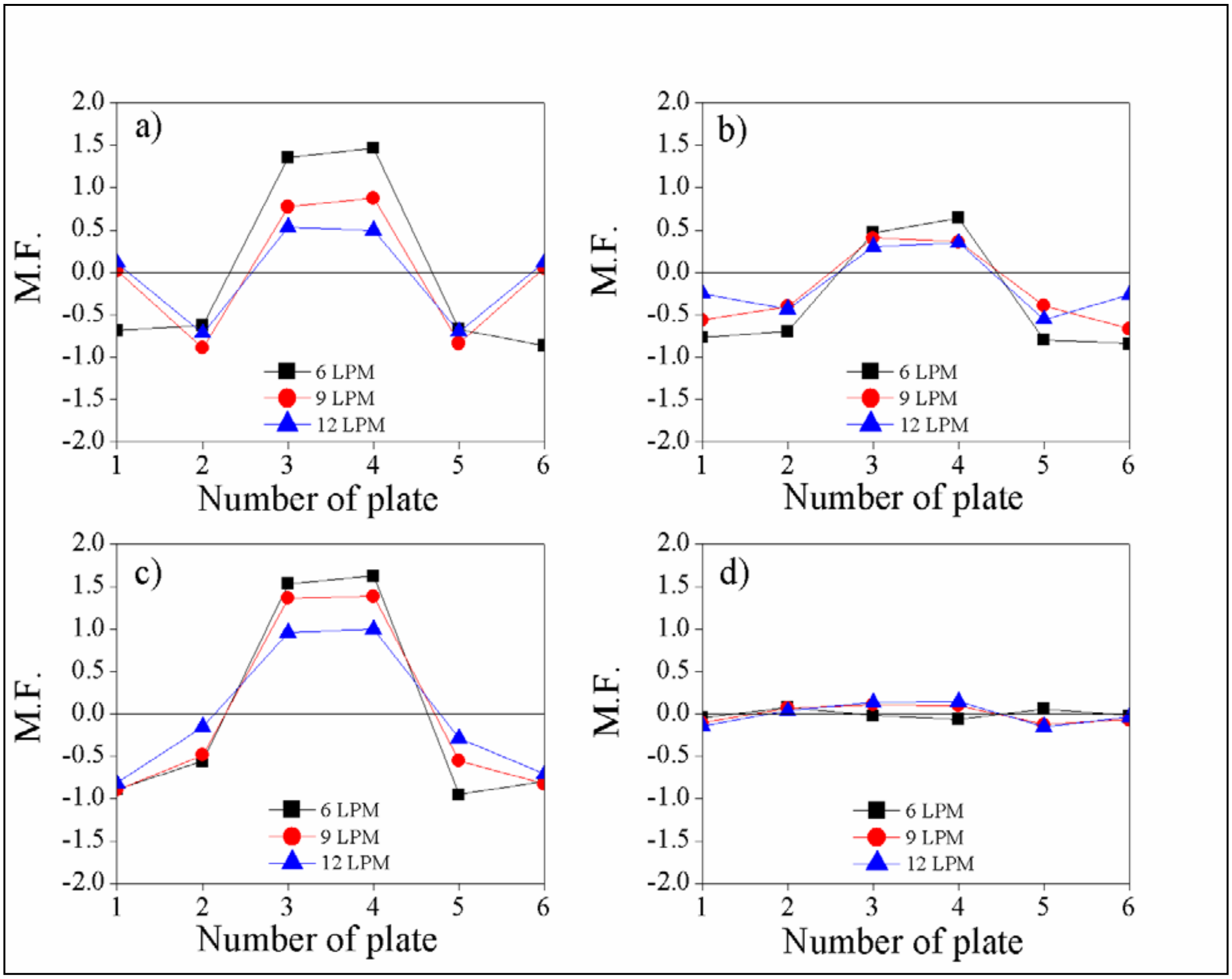

Fig. 6 Effect of the flow rate on maldistribution: a) plain tube b) spray nozzle c) perforated plate d) branch tube distributor

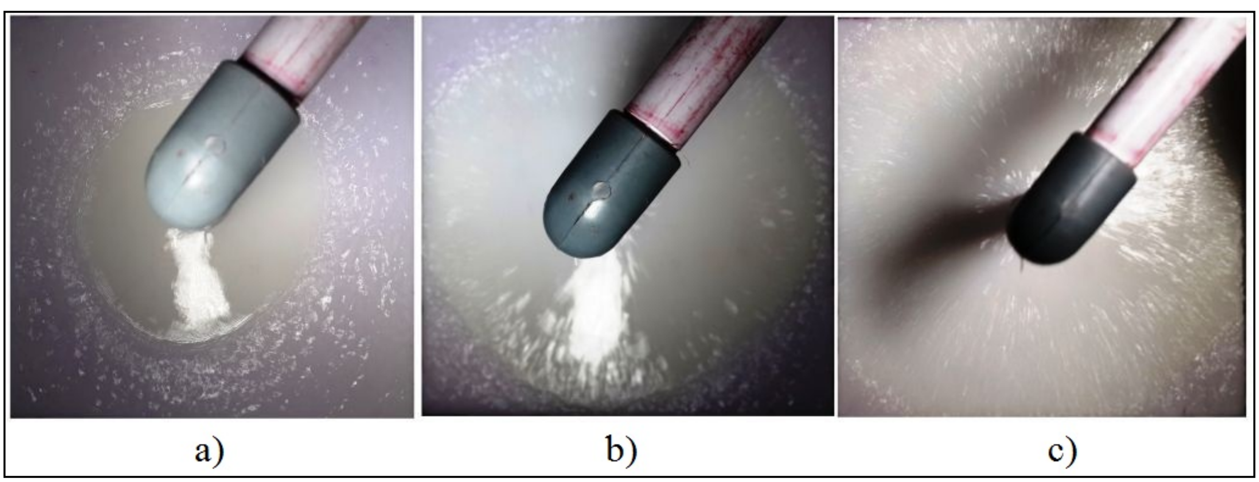

Fig. 7 Hydraulic jump for the plain tube distributor: a) 6 LPM b) 9 LPM c) 12 LPM flow rates

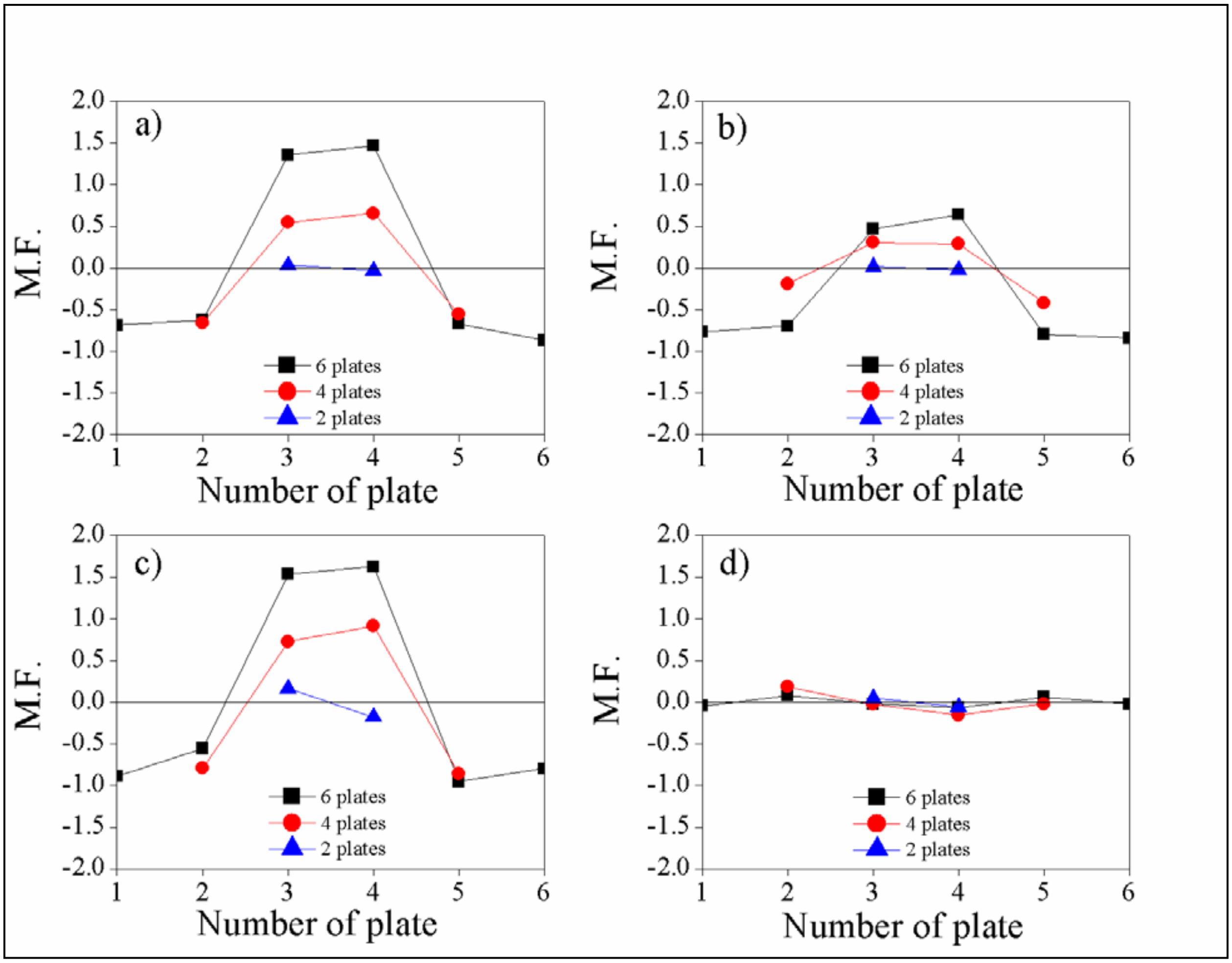

Fig. 8 Effect of the number of plates on maldistribution: a) plain tube b) spray nozzle c) perforated plate d) branch tube distributor

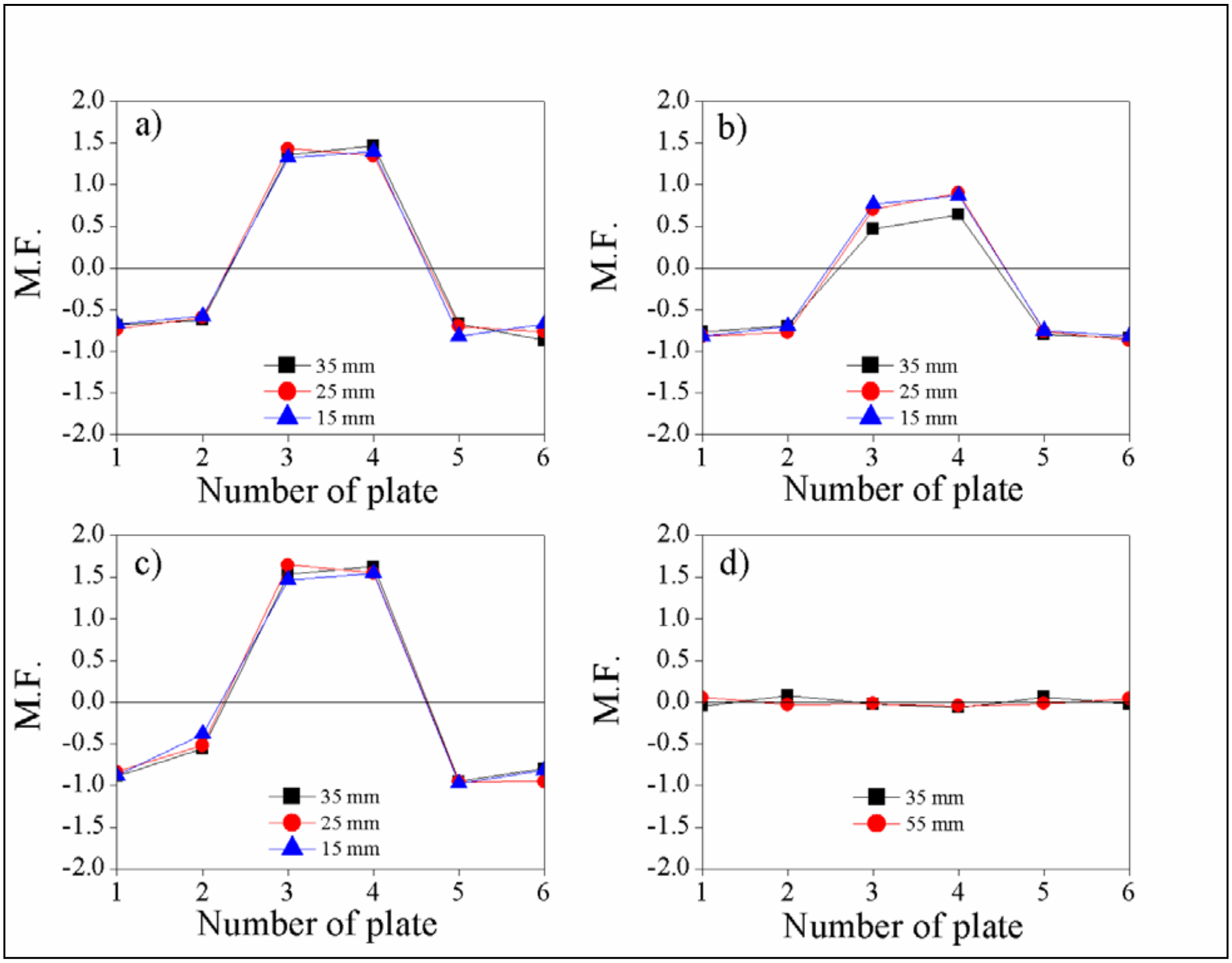

Fig. 9 Effect of the height of distributor on maldistribution: a) plain tube b) spray nozzle c) perforated plate d) branch tube distributor