CHAPTER III

HOLD UP AND PRESSURE DROP IN ABSORPTION COLUNMS
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3.1 Hold-up

When the liquid flows through a column, it coats the surface over which it flows. The quantity of liquid retained in this way in the column is known as hold-up. It is usually expressed by the fraction \( H \) (m\(^3\) liquid retained/m\(^3\) volume of column). A large fractional liquid hold-up is disadvantageous, as: (i) large liquid hold-up increases the time to establish steady operating conditions and the time to drain the column; (ii) the load on the packing support increases; and (iii) sufficient volume of the apparatus has to be provided to store the retained liquid when the column is shut down.

Liquid hold-up consists of a static component and a dynamic component. The static component is the amount of liquid held on the packing by capillary forces. It is independent of the hydrodynamic conditions and depends only on the characteristics of the packing and the liquid used (e.g. liquid density, and surface tension). The results of Shulman\(^{181}\) indicate that static hold-up depends on the properties of the surface (Roughness etc.) and must be measured experimentally.

Simmons et al\(^{182}\) concluded that operational hold-up is practically independent of the packing. This was not
confirmed by latter works with more varied types of packing. Mayo et al. assumed that the entire hold-up consisted of a liquid layer on the packing surface. They attempted to show that this layer rapidly assumed a maximum thickness as the liquid flow rate was increased to appreciable values, after which its thickness did not increase with increased liquid circulation through the packing. They attributed the continued increase in hold-up with the increased liquid flow to the initial incomplete wetting of the liquid surface which progressively increased with increased flow rate. Furnas also assumed that the liquid hold-up was represented by film flow over the packing surface which varied linearly with the film thickness. These authors also recognised the fact that wetted area increased with the rate of liquid flow. Their original assumption was justified to a certain extent by the fact that the increase in film thickness and wetted area has the same effect on \( k_{oa} \).

Elgin and Weiss questioned the fact that the hold-up consisted only of a liquid film on the packing surface over the entire range of liquid flow. They concluded that liquid hold-up in the interstices of the packing at points of contact constituted a major contribution to total hold-up, especially at substantial rates of liquid circulation. The data showed that curves of hold-up against gas velocity (with liquid rate
constant) rise sharply at loading points as do the analogous curve of pressure drop against velocity. Elgin and Jasaer concluded that depending upon the rate of liquid circulation, hold-up arises from three sources, namely: (i) contact points, (ii) film flow on the surface, (iii) liquid in the free space. At only low flow rates the first type exists. At intermediate flows the first two types exist. Finally, at high flows all the three add up to the total. It is evident from this that number of contact points play an important role in hold-up and that the relation between hold-up and contact area in gas liquid transfer process in packing is complex. According to these authors the difference in the behaviour of different packings will depend upon the relation between number of contact points, packing area and free space. These workers also noted that in their studies of 1/2" and 1" Berl saddles and 1/2" and 1" Raschig rings, operational hold-up appeared to be independent of gas velocity until the region of loading was reached.

Lava correlated the work of many authors for air-water system and found that the hold-up below loading varies as \( L^{0.6} \). Shulman measured the operational and inherent hold-ups from 1" Raschig rings and Berl saddles below the loading point and found that operational and inherent hold-ups are functions of liquid rate, liquid viscosity, liquid density and surface tension. Thoens and Kramers showed that the
The contribution of static hold-up towards mass transfer is limited. Turner et al.\textsuperscript{201} also investigated the nature of liquid hold-up. They reduced the situation to the most simple case of two neighbouring touching spheres. Nas\textsuperscript{106} used radiological methods to study hold-up and flow distribution.

Gelbe\textsuperscript{78} has presented a new correlation of liquid hold-up in packed bed, the total liquid hold-up and adherent hold-up of 14 different types and sizes of packing (consisting of Raschig rings, wire mesh rings, metal lessing rings and wire spirals) were measured with a scale, using six different liquids. The new equations are well confirmed by the result of Shulman\textsuperscript{181}. The maximum deviation is less than 12\%. This correlation enables static and operating hold-up to be calculated separately.

Kolar\textsuperscript{121} presented a relation between liquid hold-up and gas flow rate for spherical packing. The equation has been developed from a theoretical model and is valid in the range above the loading point. A similar equation was found to be valid in the range below the loading point. Tichy\textsuperscript{198} in a recent article has simplified the equation proposed by Kolar\textsuperscript{121} and modified it for packings other than spherical. This equation was tested on the data obtained by Shulman\textsuperscript{181}. In order to use this correlation, the gas flow rate at flooding and liquid hold-up at zero gas rate must be known.
Krause measured static and dynamic hold-up in a column packed with ceramic Raschig rings and concluded that mass flow velocity of the vapour, height of packing, and column diameter did not have sufficient effect on dynamic hold-up. The effects of mass flow velocity of liquid and equivalent diameter of Raschig rings on dynamic hold-up were determined. Equation relating static hold-up to equivalent diameter and dynamic hold-up to mass flow velocity of liquid has been presented and compared with published correlation.

3.2 Pressure Drop

Pressure drop measurements in the gas stream of wetted wall column under various geometric and flow conditions have been reported by various authors. Zhivakiin and Volgin have reported work on pressure drop for downward cocurrent gas/film flow. Bennett and Thornton, Calvert and Williams, Hewitt and Co-workers, and Mährenholtz have made numerous studies on upward cocurrent flow. For countercurrent flow studies have been reported by Clayton, Feind, Jackson et al., Kamei and Oishi, and Thomas and Portalski. Small static pressure drops occurring in wetted wall equipment in the absence of a net gas flow due to the entraining action of the liquid film surface has also been reported in the literature.
Brauer\textsuperscript{19} carried out a detailed analysis of the flow of smooth films and gas streams inside vertical tubes. This work dealt with all the cases of film/gas flow (countercurrent, upward cocurrent and downward cocurrent) in a unified manner by plotting the calculated results in the form of $|f|$ as a function of $Re'_g$, where $|f|$ is the absolute value of dimensionless pressure drop in the gas stream:

$$|f| = \frac{2 \tau}{\mu_{gas}(\bar{u}_{gas})} = \frac{2(\Delta P)(R-b)}{\mu_{gas}(\bar{u}_{gas})^2 L} \quad \text{----- (3.1)}$$

$R$ is tube radius, $b$ is film thickness, $L$ is length of the column and $\Delta P/L$ is the pressure drop per unit length of wetted tube. $Re'_g$ is defined as:

$$Re'_g = \frac{2(\bar{u}_{gas})}{\mu_{gas}} \frac{2(R-b)}{\mu_{gas}} \quad \text{----- (3.2)}$$

where $\bar{u}_{gas}$ is mean velocity of the gas, $\mu_{gas}$ is kinematic viscosity of gas. Limiting values of the gas stream pressure drop have been obtained for the various flow regimes.

Feind\textsuperscript{65} showed later that the effect of an interfacial shear $\tau_1$ due to a countercurrent gas stream is to increase the film thickness for a vertical wall in the ratio,

$$\frac{b}{b_0} = \left\{ 1 - \frac{3\tau_1}{2 b} \right\}^{1/3} \quad \text{----- (3.3)}$$

where $b_0$ denotes the value in the absence of a gas stream.
Flooding commenced when

\[ \frac{T_1}{b \ell g} = \frac{2}{3} \]  \hspace{1cm} \ldots \ldots \ldots (3.4)

It was also found that the ratio of the wall shear stress \( T_w/T_{w0} \) decreases until \( T_1/b \ell g = 1/2 \) and then increases sharply. The surface velocity in the presence of the gas stream was shown to be

\[ u_s = \frac{6}{5} b^2 (1/2 - \frac{T_1}{b \ell g}) \]  \hspace{1cm} \ldots \ldots \ldots (3.5)

and it was deduced that the ratio of the surface velocity to the mean velocity of the film was given by,

\[ \frac{u_s}{\bar{u}} = 3 \left(1 - \frac{2 T_1}{b g (\sin \theta)}\right) \left(2 - \frac{3 T_1}{b g (\sin \theta)}\right) \]  \hspace{1cm} \ldots \ldots \ldots (3.6)

Above theoretical treatments assume that the pressure drop per unit length of the wetted-wall column is a constant quantity, that is, the gas and liquid streams are both in steady state flow with no changes in their velocity profiles in the direction of flow of each phase. In many cases the experimental pressure gradient reported in the literature have been obtained by dividing the pressure drop obtained over the whole length of the column with the height of the column, which is valid only so long as the pressure gradient is constant over the whole length of the column. Some studies on countercurrent flow in upward cocurrent flow, and in downward cocurrent flow.
have shown that the pressure gradient is not always constant in the direction of flow of the gas, due to change in the shape of the gas stream velocity profile and to changes in energy on accelerating or decelerating the liquid film near the inlet. Until the effect of these variations is accurately determined it is redundant to apply the above theory to the experimental results which may be valid only for the specific column dimensions investigated.

An interesting observation made during the studies of pressure drop in dry and wetted tube is that the pressure drop in wetted tube with wavy flow of liquid is considerably larger than in the case of flow through the dry tube at the same velocity. In an attempt to explain this effect, Laird investigated gas flows along tubes with flexible walls in which sine wave oscillations could be induced. It was concluded that a large part of the increase in the pressure drop over the value for a smooth tube was due to changes in the gas stream profile. Later measurements by Laird et al. in tubes with wavy stationary walls showed that the pressure drop in this case was not greatly in excess of the value for a smooth tube from which it was concluded that the boundary shape alone could not be the cause of the large increase in the pressure drop in columns wetted by wavy films. Kombeev and Zhavoronkov carried out similar studies for both long-wave and short-wave stationary wall roughnesses and pointed out that in wetted wall columns the pressure drop increase would be greater than in a
tube with stationary solid waves on the walls, due to the moving, irregular and deformable nature of the roughness elements. In the case of countercurrent gas/film flow, Feind has suggested that the thin layer of gas entrained at the surface of the liquid film (to satisfy the conditions of zero slip) must travel in a direction opposite to the main gas stream so that the effective gas velocity gradient at the interface (and hence the pressure drop) will be increased.

Attempts have been made to characterise the effects of the interfacial wave on the gas stream by calculating an equivalent sand roughness for the wavy interface from velocity profile measurements in the gas stream. Gill et al. have shown that the effect of a wavy film surface on a gas stream in contact with it is not the same in some respect as that of a solid rough wall. One complication of regarding the film surface as a rough surface relative to which the gas stream moves is that, in this case the "roughness elements", are themselves in motion relative to the "wall".

Thus, from above discussion it can be seen that our knowledge of the pressure drop and the interfacial shear stress in the gas stream of a wetted wall column is very unsatisfactory at present. As the pressure drop values are small as compared to other absorption equipment such as packed towers, bubble-cap tower etc., there is an urgent need for a versatile manometer which can measure small pressure drops accurately.
3.3 Experimental Methods for Determination of Hold-up and Pressure Drop

Different methods for experimental determination of hold-up are: (i) Interception of wetting liquid, (ii) Weighing method, (iii) $\gamma$-radiation methods.

(i) Interception Method:

The interception method is probably the most widely used method of measuring hold-up. It consists simply of isolating a section of liquid film, allowing the liquid in this section to drain and measuring its volume. To avoid excessive shock, it is often advisable to divert the main flow stream around the measurement section via an alternative path. Provided proper attention is paid to the design of the device, the interception method can give very accurate and reproducible results. This fact has been illustrated by the results obtained by Hewitt and Lovergrove\(^98\) for falling film flow. With this method only dynamic hold-up can be measured. In this method it is however not certain whether during the collection of the liquid from the column, all the liquid corresponding to dynamic hold-up has run out.

(ii) Weighing Method:

The weighing method is similar in principle to the interception method except that arrangements are made actually
to weigh the liquid held up in the experimental section during operation. Kamei and Uishi\textsuperscript{114} have used this method for falling films both with or without a counter-current gas flow. The principle has also been used by Shulman et al\textsuperscript{131} and Hewitt\textsuperscript{98} to measure the hold up in packed columns.

The precautions to be taken with this method include care in the design of the equipment particularly the entrance and exit to the experimental section to ensure adequate sensitivity and the absence of any systematic errors due to friction and forces induced by the supports. A null deflection balance arrangement should be employed and a force balance carefully formulated to account for all the forces imposed on experimental section. Under conditions of no gas flow very good accuracy, comparable to that of the interception method is possible. Because of frictional forces induced, the method is not recommended for conditions with gas flow except for the case where these forces act on a horizontal plane.

(iii) \( \gamma \)-Radiation Method

In this method intensity of \( \gamma \)-radiations passing through the wetted and unwetted column is measured to determine the liquid hold up. With this method it is possible to measure the liquid distribution over the height and cross-section of the column. This method however requires specialised equipment.
Table 3d — Main Design Features and Defects of the Various Manometers

<table>
<thead>
<tr>
<th>Type of manometer</th>
<th>Main design features</th>
<th>Defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parkin (I)</td>
<td>Two glass cups connected by means of a rubber tubing; null point obtained by moving one cup through a measured distance</td>
<td>1-6</td>
</tr>
<tr>
<td>Parkin (II)</td>
<td>Same as above except that the movable limb is an inclined tube</td>
<td>1, 3, 4.4</td>
</tr>
<tr>
<td>NPL</td>
<td>Null point reading obtained by readjusting the position of a meniscus, as in the central vessel of Chattock tilting manometer</td>
<td>1, 2, 6, 5</td>
</tr>
<tr>
<td>Engineers'</td>
<td>Null point accurately obtained by optical illumination of a fixed point</td>
<td>3, 3.4, 4</td>
</tr>
<tr>
<td>Macmillan</td>
<td>Same as Parkin (II) except that the movable limb is a reservoir instead of an inclined tube</td>
<td>1, 2</td>
</tr>
<tr>
<td>Bradshaw</td>
<td>Inclined tube rigidly fixed to the reservoir; null position obtained by raising or lowering the table on which the reservoir rests</td>
<td>7</td>
</tr>
<tr>
<td>Present authors'</td>
<td>A cylindrical reservoir in which a piston moves up and down; null point attained by the movement of this piston, which is governed by circular movement of a suit of complications of arresting circular movement of piston eliminated</td>
<td>all</td>
</tr>
</tbody>
</table>

*Details of defects given in text.*

Fig. 1 — Main design features of various micromanometers
(1) Parkin (I); (2) Parkin (II); (3) NPL; (4) Engineers'; (5) Macmillan; (6) Bradshaw; and (7) authors' micromanometer

3.1 Design features of various manometers
Pressure Drop:

Accurate measurements of pressure drop in helical wire column, wire gauge column and wetted wall column necessitate the design of a micromanometer with a long range. Many designs are described in the literature and all of them utilize the basic principle of balancing a pressure difference by the weight of a column of known density, but differ in respect of the methods adopted for increasing their sensitivity. The pressure balance is achieved by obtaining null point reading on raising one limb of the manometer relative to the other limb. Table-3.1 gives a comparative idea of the means used to obtain the null point reading. The main design features of various manometers are shown in Fig.3.1.

The common sources of error in the design and operation of such micromanometers are:

1. When one limb is moved with respect to the other, the average cross-sectional area of the connecting rubber or plastic tubing is altered.

2. Due to the comparatively large volume of the connecting tube, a change in cross-sectional area significantly affects the volume of the fluid in the reservoir.

3. Any change in the angle of the inclined tube alters its calibration.
4. A large time lag makes the attainment of steady state unduly slow.

5. Zero reading is sometimes unstable.

6. Null point reading is not sufficiently accurate in some cases.

7. The manometer may have low sensitivity.

The first useful long range manometer designed by Parkin\textsuperscript{155a} suffered from all these drawbacks. Some of these defects were later removed by replacing one of the cups with an inclined tube. The National Physical Laboratory manometer\textsuperscript{152} has a similar construction, but has a modified arrangement for obtaining null point reading. Another design\textsuperscript{147} incorporates a still better method for indicating the null point as a fixed point illuminated in the centre of the reservoir, so that its position coincides with that of its reflected image. An accuracy of up to 0.0004 in. of water is thereby obtained.

Macmillan\textsuperscript{139} decreased the time lag during null point determination by adjusting the reservoir height. Bradshaw\textsuperscript{17} succeeded in eliminating most of the common sources of error, including cosine error resulting from tilting of the reservoir, by making the bottom of the reservoir spherical and replacing the pointed resting point by a flat table. The axis of rotation of the table passes through the zero position of the meniscus in the inclined tube, and hence there is no error due to inclination of meniscus.
For a good design, the internal air volume of a manometer should be small enough to provide a short time lag, yet it must have a high sensitivity to give accurate readings at low air speed. The rate of change of zero reading should be low. In actual practice, these conditions are only partially met. The sensitivity expression for such a manometer is:

$$\frac{dx}{dt} = \frac{1}{(a/A) + \sin \theta} \quad \ldots \ldots (3.8)$$

For sensitivity to be large, $(a/A) + \sin \theta$ should be small. This can be achieved by increasing the reservoir/inclined tube area ratio. By increasing the area of the inclined tube, sluggishness can be reduced, but at the cost of a less sharp meniscus. In addition, a more narrow tube offers greater resistance to air flow, as pressure drop, according to the well known Hagen-Poiseuille's equation, is inversely proportional to the fourth power of the internal diameter.

$$v = \frac{\pi (p_1 - p_2)r^4}{8\mu z} \quad \ldots \ldots (3.9)$$

An increase in the reservoir area results in greater sensitivity at the expense of a larger time lag. Sensitivity may be increased by decreasing the angle of inclination. In the limiting case, i.e., when $\sin \theta = \frac{a}{A}$, the sensitivity is infinitely large, but the meniscus is completely unstable.
Apart from the considerations pertaining to sensitivity, the effectiveness of a manometer depends also on the rate of change of zero reading. Temperature differences affect this reading because of (1) thermal expansion of the reservoir and the manometer fluid, and (2) change in surface tension due to change in temperature. The first of these can be represented by the equation:

$$\Delta L = V(\beta - 2\alpha) \Delta T/A \quad \ldots \ldots \ (3.10)$$

and the second by

$$\Delta L = 2(\sigma_1^\prime/\ell_1 - \sigma_2^\prime/\ell_2) \pi r \quad \ldots \ldots \ (3.11)$$

where $\alpha$ is coefficient of linear expansion of the reservoir and inclined tube, $\beta$ is coefficient of volume expansion of the liquid, $\ell$ is density of the manometric fluid, and $r$ is radius of the tube.

An optimum design is obtained when these two effects mutually counter-balance each other, i.e., when

$$W(\beta - 2\alpha)\Delta T/A = 2(\sigma_1^\prime/\ell_1 - \sigma_2^\prime/\ell_2) \pi r \quad \ldots \ldots \ (3.12)$$

Thus, if the dimensions $V, r$ and $A$ of the manometer are perfectly matched with the properties $V, \ell, \beta$ of the manometric fluid in accordance with the above equation (3.12), the drift of the zero reading due to temperature will be nil.
Change in zero reading may also be due to tilting of the reservoir. This change affects the liquid meniscus in the reservoir as well as in the side tube. As shown by Bradshaw\textsuperscript{17}, inclination of the reservoir does not affect the liquid level, provided its cross-section is symmetrical about an axis of tilting. Change in inclination of the meniscus in the side tube becomes more pronounced when this tube is rigidly fixed to the reservoir. No difficulty arises at the inclined tube and if it is inclined, one must arrange that the axis of rotation intersects the axis of the tube at the effective position of the meniscus. The error introduced is 
\[ \delta l \sin \alpha (1 - \cos \theta) \]
where \( \delta l \) is the distance between the bottom of the meniscus and the effective position.

A new design for sensitive wide range manometer which eliminates all such errors and is at least 10 times as sensitive as Bradshaw manometer has been incorporated as a part of the present thesis (see Chapter VI).