Spray impact onto deep liquid layers: deformation of air-liquid interface, secondary spray and air bubble entrainment

Davood Kalantari, Ilia V. Roisman, Cameron Tropea
Fachgebiet Strömungslehre und Aerodynamik, Darmstadt University of Technology
Petersenstraße 30, D-64287 Darmstadt, Germany, Tel. +49 6151 16 2854
Email: d.kalantari@sla.tu-darmstadt.de, roisman@sla.tu-darmstadt.de, ctropea@sla.tu-darmstadt.de

ABSTRACT
In this work, an experimental study of liquid spray impact onto a deep liquid layer is presented. A high-speed CCD camera has been used to measure the deformation of the air-liquid film interface and the distribution of the air bubbles inside the deep liquid film. Two different configurations of a phase Doppler instrument have been used to measure drop size and two components of velocity directly above the film as well as the size and two components of velocity of the air bubbles inside the deep pool.

Keywords: spray impact; deep liquid film; secondary spray; air bubbles.

1. INTRODUCTION

Hydrodynamics of gas bubbles in a liquid flow is of importance in many technical and industrial applications, such as; cavitation damage due to collapse of gas bubbles near a rigid wall, drag reduction of submerged bodies by micro-bubble injection at the boundary layer, aeration downstream of a free discharge Howell-Bunger valve, and nuclear reactors [1-7]. One source of bubbles is the impact of a spray on a deep liquid layer. In general, spray impingement on deep liquid layers is characterized by the three different structures: 1) deformation of the air-liquid film interface 2) generated secondary spray, and 3) the entrainment of the air bubbles inside the liquid film. When an inertial spray impacts onto a deep liquid film, many micron-size air bubbles are ejected and appeared inside the film. The average size of such bubbles corresponds to the average impacting droplet size in the spray. The bubbles moving downward and upward have different normal velocity components. Similar phenomenon, i.e. entrainment of many very small air bubbles, was already demonstrated by Esmailizadeh and Mesler, see e.g. [8, 9], known as the Mesler bubble entrainment mechanism. They attributed this type of entrainment for small droplets with small impact velocities, but the impact velocities in the present case are relatively large, in the range of 6, 15 m/s.

Velocity fluctuations inside a liquid pool resulting from the interaction of a bubble with a vertical wall have been studied by Moctezuma et al. (2005) [6]. The movement and fluctuation of the bubbles inside the film can significantly change the heat transfer between the liquid film and the ambient gas.

The dynamics of a gas bubble in a continuous media depend on several dimensionless numbers; Reynolds number \((Re)\), Eötvös number \((Eo)\) and Morton number \((Mo)\) defined as; \(Re = \frac{\rho u d_b}{\mu}\), \(Eo = \frac{(\rho_g - \rho_l) g d_b^2}{\sigma}\) and \(Mo = (1 - \frac{\rho_g}{\rho_l}) g \mu_l^2 / \sigma^3\), respectively. Here \(\rho_l\) is the density of the bulk liquid, \(\rho_g\) is density of the gas bubble, \(\mu_l\) is the viscosity, \(\sigma\) is the surface tension, \(d_b\) is the bubble diameter, and \(u\) is the relative bubble velocity.

The present work is an experimental study of the spray impact onto a deep liquid film under various well-defined spray conditions. Characterization of different aspects of spray impact onto deep liquid films, especially characterization of the micron-size bubbles is presented.

2. EXPERIMENTAL SET-UP

The experimental set-up used in this work is pictured in Fig. 1. The spray was created using two different full-cone nozzles from Spraying System Co. and two different hollow-cone nozzles from Delevan Co., operated at pressures between 3 and 7 bar. Both flow rate and pressure during the experiments were variable and measured. A transparent box with dimensions 100 × 100× 100 mm³ has been used as a deep pool.

The nozzles were placed at different positions above the undisturbed air-liquid film interface (see Fig.2). The \(X\) coordinate of the nozzle has been varied in the range \(X_{\text{nozzle}} = -20 \text{ mm to } -50 \text{ mm}\).

![Fig.1](image.png): Photograph of experimental set-up used in this study.
To characterise the spray, a dual-mode phase Doppler instrument from Dantec Dynamics was used, comprising a transmitting optics with a 310 mm focal length, a receiving optics with a 310 mm focal length, and an “A” type mask at 34° or 90° scattering angle for measuring impacting spray or air bubbles, respectively. By using a dual-mode configuration both normal and tangential velocity components of each individual droplet or bubble and its diameter were measured.

The ingoing and outgoing droplets or ejecting and rising bubbles are distinguished using the sign of the normal velocity component, i.e. positive \( u \) denotes an impacting droplet or ejecting bubble and a negative \( u \) denotes a secondary droplet or rising bubble. The overall size distributions were corrected for the size dependent detection volume cross-section using the standard system software.

Alternatively, the deformation of the air-liquid film interface has been observed using a high-speed video system. The average deformation of the air-liquid film interface is obtained by averaging over several instantaneous images after first removing the reference interface image. Additionally, the same high-speed camera has been used to observe the distribution of the large and small air bubbles inside the deep pool, as well as the concentration of the air bubbles within the whole volume of the container.

![Fig.2: Coordinate system for the spray and deep pool.](image)

### 3. RESULTS AND DISCUSSION

The paper deals with three different aspects of spray impact onto deep liquid layers:
- deformation of the air-liquid film interface due to the hydrodynamic pressure gradient exerted from impacting drops,
- the generation of a secondary spray, and
- the air bubble entrainment into the liquid film.

In the following sections, each aspect of the spray impact onto a deep liquid layer will be individually presented in more detail.

#### 3.1. Deformation of air-liquid film interface under spray impact

Deformation of the air-liquid film interface in spray impact phenomenon is important for estimation of the average hydrodynamic pressure exerted from impacting drops which is one of the important integral parameters of the spray.

In the case of an inertial dominant spray impact onto a deep liquid pool, the shape of the air-liquid film interface is determined primarily by the hydrodynamic pressure exerted on the interface, defined by

\[
P = P_g + P_{hyd}
\]

where \( P_g \) is the pressure exerted from the ambient gas (air flow) onto the air-liquid interface and \( P_{hyd} \) is the hydrodynamic pressure exerted from impacting droplets.

The hydrodynamic pressure produced by the impinging droplets is the main source responsible for the surface deformation. An exemplary image of such deformation is presented in Fig. 3a for a given nozzle pressure and nozzle height and for different nozzle pressures in Fig.3b. In this picture, results of deformation generated by a hollow-cone nozzle in presented. It is shown that the diameter of deformed interface increases with the nozzle pressure due to the increase of the spray cone angle. Moreover, increasing the nozzle pressure leads to a smoothing of the deformed interface in this picture, see Fig.3b.

The hydrodynamic pressure is the component of the momentum tensor flux density of the spray normal to the surface [10]. In the impingement region of spray impact onto a deep pool, the hydrodynamic pressure is generated by the momentum change of the impacting droplets. Considering the simplest one-dimensional case, the average hydrodynamic force exerted on a surface by an impacting spray can be given by

\[
F_{hyd} = \frac{(m_b \cdot u_b - m_a \cdot u_a)}{t}
\]

![Fig.3: a) Exemplary deformation of the air-liquid film interface due to spray impact, and b) film interface for different nozzle pressure.](image)
Defining the volume flux of the impacting drop by $q = \frac{V}{t}$, Eq. (2) can be rewritten as

$$F_{\text{hyd}} = \rho \left( q_b \cdot u_b - q_a \cdot u_a \right)$$  \hspace{1cm} (3)

Consider, for example, a case of ideally elastic drop impacts onto a rigid wall. In this case the rebounding drop has the same velocity and trajectory as that of the primary drop, i.e. $d_a = d_b$ and $u_a = -u_b$; then the hydrodynamic pressure ($P_{\text{hyd}} = F_{\text{hyd}} / A$) exerted on the wall by a rebounding drop is

$$P_{\text{hyd Reb}} = 2 \rho \dot{q}_b u_b$$  \hspace{1cm} (4)

where $\dot{q}_b$ is the volume flux density of impacting droplets in the direction normal to the wall surface. The same procedure for the case when all the droplets are deposited on the wall gives

$$P_{\text{hyd Dep}} = \rho \dot{q}_a u_b$$  \hspace{1cm} (5)

In the case of a spray impact onto a deep liquid pool, some droplets rebound, most others deposit in the film, whereas some of them partially splash or generate an cylindrical ejected film after a cavity collapse, therefore a constant factor $\beta$ depending on the number of rebounding or depositing droplets should be considered for hydrodynamic pressure exerted on the wall by an impacting spray, defined as

$$P_{\text{hyd}} = \beta \cdot \rho \dot{q}_b u_b : 1 < \beta < 2.$$  \hspace{1cm} (6)

For a spray, the coefficient $\beta$ can be estimated based on the number of ejected droplets from the wall in comparison to the all primary droplets, defined as

$$\beta = 1 + \frac{\dot{N}_d}{\dot{N}_b}$$  \hspace{1cm} (7)

Based on the results presented in the next section (Fig. 6a), it can be assumed that the normal velocity component of the secondary droplets is negligible in comparison with the normal component of the impact velocity. This means that most part of the momentum of an inertial impacting spray is transferred into the deep pool resulting in the deformation of the air-liquid film interface, velocity field and velocity fluctuations inside the film and ejection of the air flow into the liquid layer. Therefore in the case of a normal spray impact onto deep liquid pools a coefficient value of $\beta = 1$ can be assumed.

An exemplary image showing the maximum deformation of the air-liquid film interface under an inertial impacting spray is illustrated in Fig. 4.

The maximum depth, $L_D$, of the of the liquid deformation corresponds to the position where the hydrodynamic pressure is balanced by the hydrostatic pressure $\rho g L_D$.

![Fig. 4: Maximum depth of the air-liquid film interface deformation under spray impact.](image)

![Fig. 5: Maximum air-liquid film interface deformation as a function of hydrodynamic pressure exerted from impacting spray.](image)

Experimental results indicate that the maximum deformation of the air-liquid film interface ($L_D$) increases significantly with the hydrodynamic pressure of the impacting spray. This result is presented in Fig. 5, indicating that the maximum deformation of the film surface correlated linearly with the hydrodynamic pressure of the impacting spray, confirming the above statement. In this figure, $P_{\text{hyd}}$ is computed applying the Eq. (6) to the Phase Doppler measurement results.

3.2. Formation of the secondary spray due to spray impact onto deep liquid layers

The distribution of droplets in the impacting spray (the diameter and two velocity components) has been characterized using the phase Doppler instrument. The detection volume has been located above the water surface. The primary and secondary droplets are distinguished by the sign of the normal-to-the-surface velocity component. The same experimental method is used as in the study of spray impact onto a rigid wall [11, 12].

Normal and tangential velocity components before and after impact are illustrated in Fig. 6a, and b for a low impact velocity condition. Note that in the case of a high inertial impact condition, i.e. high impact velocities, measurement of the secondary spray exactly above the interface was difficult. Results of this study indicate that the normal velocity component of the ejected droplets is very poorly correlated with the normal component of impingement velocity (Fig. 6a). On the other hand the
tangential component of the ejection and impinging velocities relatively correlated with one another (Fig. 6b). In this case the ratio of tangential component of velocity after to before impact ($v_u/v_n$) is about half of this ratio for spray impact onto rigid walls.

3.3. Air bubble entrainments due to spray impact onto deep liquid layers

A new aspect of air bubble entrainment in liquid film has been distinguished during the measurements: entrainment of many very small micron size air bubbles in the deep part of liquid films distributed in a cone shape (Fig.7b). Note that these bubbles cannot be seen by illumination of the film with a normal light, as shown in Fig. 7a.

A close-up view of such bubbles is presented in Fig. 8 for an exemplary nozzle height and a given depth of the liquid film for different atomizing pressure. These exemplary results indicate that the number of bubbles (bubble concentration) increases significantly with the atomizing pressure, i.e. impact Weber number.

Results obtained in this figure clearly indicate that mechanism of the air bubble entrainment by a spray impact, i.e. impact of multiple micron-size droplets with high velocity, differ significantly with the mechanism of bubble formation due to the cavity collapse in a single drop impact onto a deep liquid layer, since in the case of spray impact, the size of the air bubbles and impacting droplets fall in the same range (the same order of magnitude), whereas in the case of a single drop impact, the size of the air bubble is much smaller than the size of impacting droplet.

The mechanism of drop impact and the subsequent bubble entrainment is explained in the study [13]. In this experimental work the impact and penetration of a rigid disc has been visualized. Such impact leads to the creation of a cavity, its collapse and creation of a bubble.

With this assumption, the similarity of the bubble size with impacting droplets can be explained. The average size of these bubbles mostly falls in the range $[25, 45] \mu m$ under the nozzle exit centreline ($z=0$) independent of the film depth, despite the fact that the mean size of the impacting droplets varies in the range $30 \leq d_{\text{inj}} \leq 40 \mu m$. These micron size bubbles move with very small velocities inside the film, of the order of $O(10)$ cm/s for ejected bubbles and $O(1)$ cm/s for upward rising bubbles.

The number concentration of the air bubbles at each measurement point inside the film depends on the mass flow rate of the air entering into the liquid medium, which depends on the number concentration of the impacting droplets. Results show that the number of air bubbles inside the film increases significantly with the atomizing pressure (Fig.8). Larger bubbles are formed close to the air-film interface, see Fig.3a.

Probability density distributions of the bubble size (pdf) for different impact Weber numbers are presented in Fig. 9a, b, c, and d. In these figures bubble count at each bin (bubble size class) is normalized by the total bubble count. It is interesting that the normalized pdf of the bubble counts presented in Fig.9 is independent of the impact Weber number, i.e. these pdfs have the same mean value and same range. On the other hand, these pdf distributions are very similar to the pdf distribution of the impacting droplets.
The probability density distribution of the bubble size normalized by the total bubble count \( N_b/ N_{b\text{-total}} \) can be expressed by a Gaussian distribution function defined as

\[
N_b / N_{b\text{-total}} = A_b + \frac{A_1}{\sigma_b \sqrt{\pi / 2}} \exp \left[ -2 \left( \frac{d_b - \overline{d}_b}{\sigma_b} \right)^2 \right]
\]

where \( N_b \) is the bubble count per bin, \( N_{b\text{-total}} \) is the total bubble count during the acquisition time, \( d_b \) is the average bubble size, \( \sigma_b \) is the standard deviation of the bubble size, and \( A_b \) and \( A_1 \) are constant values.

The constant coefficients \( A_b \) and \( A_1 \) fall within the range \( 8.7 \times 10^{-4} \leq A_b \leq 2.4 \times 10^{-3} \) and \( 2.21 \leq A_1 \leq 2.45 \), respectively for conducted measurements in this study. Total bubble count during the acquisition time defined as

\[
N_{b\text{-total}} = f_b \cdot t_{aq}
\]

where \( f_b \) is frequency of the air bubbles at each measurement point and \( t_{aq} \) is the total acquisition time.

Results indicate that the frequency of moving bubbles at each measurement point increase with the atomizing pressure, i.e. impact Weber number, see Fig. 10. A simple correlation for the frequency of bubbles passing the measurement point as a function of impact Weber number and depth of film is obtained as

\[
f_b = a_1 \ln(We_b) + a_2 x + a_3
\]

where \( a_1 \), \( a_2 \), and \( a_3 \) found to be: 6.534, -0.0366, and -21.5, respectively.

Fig. 9: Probability density of air bubbles diameter for different impact condition: \( x_{\text{centre}} = -40 \text{ mm}, x = 20 \text{ mm}, a) We=36.7, b) We=44.5, c) We=52.8, and d) We=60.

Fig. 10: Frequency of bubble count as a function of impact Weber number for different depth of fluid.

This multiple correlation is obtained for the normal spray impact condition; \( \lambda_{\text{wxb}} = We_{xb} / We_{ab} < 0.1 \), flux density of impacting spray in the range \( 0.6 \leq \rho \leq 3.5 \text{ m/s} \), mean impacting drop size in the range \( 30 \leq d_{\text{imp}} \leq 40 \mu m \), and depth of fluid in the range \( 10 \leq x \leq 50 \text{ mm} \) under the centreline of the nozzle exit.

The observation of greatly reduced bubble count inside the liquid film (in the range of \( kHz \)) in comparison with the higher frequency of the impacting droplets (in the range of \( kHz \)) suggests that each impacting droplet doesn’t generate a bubble, and there should be a combination of droplet size and droplet velocity together with the physical properties of the fluid, i.e. impact Weber or Reynolds number, which yields are higher generation probability of an air bubble under the impacting spray.

Other results illustrated in Fig. 11 indicate that the bubble count decreases significantly with the film depth at any off-axis measurement point (\( x=10 \text{ mm} \) in this figure). Such an observation can be also be made from the photograph of the air bubbles inside the film, as presented for an exemplary case in Fig. 7b.

The average size of the ejecting bubbles, i.e. bubbles moving downward, as a function of the film depth, is presented in Fig. 12 for different impact Weber numbers. Results presented in this figure indicate that the average bubble size is independent of the film depth and the impact Weber number. However in this figure, the average bubble diameter scatter around the line \( d_b = 32 \mu m \), and mostly

Fig. 11: Variation the bubble count as a function of the film depth at 10 mm off-axis from the nozzle exit centerline.
are the air bubble and liquid density, \( \rho_b \) and \( \rho_l \), respectively. The Weber number \( We \) is a measure of the momentum of the impacting droplets against surface tension forces, given by

\[
We = \frac{\rho_l g d_b^2}{\sigma}
\]

where \( d_b \) is the diameter of the droplets, \( g \) the acceleration due to gravity, and \( \sigma \) the surface tension.

In the Fig. 12, the average size of impacting droplets falls in the range of 30 to 50 \( \mu m \). Results obtained in this work indicate that the bubble size distribution is very close to the impacting drop diameter distribution; therefore they have approximately the same average value, i.e., \( d_b = d_{100} \).

In the Fig. 12, the average size of impacting droplets falls in the range of 25 to 45 \( \mu m \). An exemplary of such measurement is presented in Fig. 13 for the normal spray impact condition with the impact Weber number \( We_b = 34.8 \), \( x = 50 mm \), and \( z = 0 \).

The bubble motion inside the deep liquid layer under influence of the impacting spray is determined based on the Lagrangian approach by a combination of different forces acting on the bubble:

- Buoyancy force \( F_b \)
- Virtual mass force \( F_{VM} \)
- Pressure gradient force \( F_P \)
- Drag force \( F_D \)
- Shear induced lift force \( F_L \)

The constant rise velocity of a single bubble in a stationary liquid can be estimated by the balance of the drag force \( F_D = 0.5C_D\pi d_b^2 \rho_l u_r^2 \), and the buoyancy force \( F_b = (\rho_b - \rho_l)gV_b \) applied to the bubble. In these equations \( \rho_b \) and \( \rho_l \) are the air bubble and liquid density, respectively, \( V_b \) is volume of spherical bubbles defined as \( V_b = \frac{4}{3}\pi d_b^3 / 6 \), \( C_D \) is the drag coefficient of a single gas bubble moving inside the liquid medium, given by: \( C_D = 16/Re_b \) for \( Re_b < 0.49 \) and \( C_D = 20.68Re_b^{-0.643} \) for \( 0.49 < Re_b < 33 \), [3]. The results of these estimations are shown in Table 1.

Results presented in Fig. 14a and b for the velocity of ejecting and rising bubbles deviate extremely from the rise velocity of the bubbles in a stationary deep water pool, as presented in Table 1. The main sources of the discrepancy are in the motion of the bulk liquid generated by the spray impact and by the interaction of the rising bubbles. It is also known that the rising velocity of a single bubble depends on its diameter. For example, in the case of a very small air bubble, i.e., \( Re_b < 0.49 \), the bubble rising velocity is proportional to \( d_b^2 \), or for larger bubbles the rising velocity is proportional to \( d_b^{1.49} \), see also [3, 4]. But the results of phase Doppler measurements conducted in this study indicate that the velocity distribution of the bubbles does not depend on the diameter. This means that they behave not like an array of single bubbles but as a cloud of bubbles.

An estimation for the rise velocity of the cloud of small bubbles in a water film is given in [14] in the form

\[
u_r = \frac{1.53}{\rho_l} \left[ \frac{\sigma g (\rho_b - \rho_l)}{\rho_l^2} \right]^{1/4}
\]

This formula predicts the bubble rise velocity to be approximately 25 m/s. It is interesting that this velocity is equal to the difference between the measured velocity of the entrained bubbles (which is probably comparable with the liquid velocity) and the velocity of the rising bubbles. Meanwhile a complex term for variation of the drag coefficient in the case of multiple bubbles movement must be considered, since the expressions for drag coefficients used in (16) and (17) have been obtained for a single bubble rising in a stationary liquid and variation of the drag coefficient for multiple bubble movements is not considered in these expressions, e.g., variation of the drag coefficient due to interaction of the wakes formed behind the moving bubbles must be taken into account.

### Table 1: Air bubble rise velocity as a function of bubble size in a stationary water pool.

<table>
<thead>
<tr>
<th>Bubble size (( \mu m ))</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubble rise velocity (cm/s)</td>
<td>0.03</td>
<td>0.2</td>
<td>0.55</td>
<td>1.52</td>
<td>5.78</td>
</tr>
</tbody>
</table>

Fig. 12: Variation the average bubble size with film depth for different impact Weber numbers.

Fig. 13: Variation the average ejecting (bubbles moving downward) and rising bubbles (moving upward) size with film depth.
Fig. 14: Variation the average a) ejecting bubble velocity, and b) rising bubble velocity, with film depth for different impact Weber numbers.

Results obtained in this study indicate that in contrast to the bubble size distribution, the velocity distribution of the bubbles does not exhibit a wide distribution range. This result indicates that the bubble motion inside the deep film under spray impact condition is mostly influenced by the hydrodynamic pressure inside the film and not by the bubble size.

An exemplary image showing the high concentration region of the air bubbles inside the deep pool (Fig. 4b) indicates that the air bubbles concentrate around the axis of symmetry (x-axis) instead of dispersing throughout the entire liquid container. This observation is consistent with the tangential velocity component presented in Fig. 15. The result presented in this figure indicates that after a certain film depth inside the liquid pool, i.e. x=25 mm in this figure, the tangential velocity component of both ejecting and rising bubbles vanishes, whereas their normal velocity component doesn’t change significantly, see Fig. 14a and b. Therefore after a certain film depth, most of the bubbles lose their tangential velocity component and concentrate around the vertical axis.

This behaviour can be explained by the radial flow of the liquid induced by spray impact, as well as by the induced shear lift force acting on the bubbles in the radial direction (z-direction), i.e. perpendicular to the main flow direction, due to the velocity gradient on two sides of the air bubbles (Fig. 16), expressed as:

$$F_l = C_L A_{sb} \rho u_2 \times (\nabla \times u_1)$$  \hspace{1cm} (13)

where $C_L$ is the shear lift coefficient, assumed to be $C_L = 0.25$ in this study.

The direction of this vector is toward the higher velocity field, i.e. lower pressure side, as illustrated in Fig. 15. This force concentrates more bubbles around the vertical axis instead of dispersing them throughout the flow, as shown in Fig. 7b.

4. CONCLUSIONS

This paper presents an experimental study for different aspects of liquid spray impact onto a deep liquid layer under the well controlled experimental conditions. The maximum deformation of the air-liquid film interface correlates well with the computed value of the hydrodynamic pressure exerted onto the film interface by an impacting spray.

Results obtained in this study indicate that the average bubble size does not change significantly with the film depth and seems to be correlated with the average diameter of the impacting droplets.

Fig. 15: Variation the average ejecting and rising bubble velocity with film depth for two different impact Weber numbers.

Fig. 16: Shear lift force acting on an air bubble moving inside continues liquid film under spray impact.
Other results indicate that the impact Weber number has most influence on the frequency of the bubble formation, i.e. bubble concentration, but has no significant influence on the average bubble size or bubble size distributions.

The normal velocity component of the rising bubbles under influence of the impacting spray differs significantly from the computed rise velocity of the air bubbles inside a stationary liquid film. Based on the results obtained in this study, the normal velocity component of the rising or ejecting bubbles doesn’t change significantly with the film depth, whereas the tangential velocity component changes significantly after a certain film depth. A shear induced lift force has been introduced for this effect.

The phase Doppler measurements indicate that the rising velocity of the bubbles does not depend on the bubble diameter. We explain this behaviour by the interaction of the bubbles in the cloud.

As illustrated above, the mean measured ejecting and rising bubble size varied in the range $20 \mu m < d_b < 50 \mu m$, corresponding to an impingement Weber number in the range $30 < W_{nb} < 80$ based on the normal velocity component, and mean impact droplet size in the range $30 \mu m < d_{10b} < 40 \mu m$.

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6. REFERENCES