LIQUID JET PUMPED BY RISING GAS BUBBLES

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ABSTRACT

From observations of a stream of gas bubbles rising through a liquid, a two-phase mathematical model is proposed for calculating the induced turbulent vertical liquid flow. The bubbles provide a large buoyancy force and the associated drag on the liquid moves the liquid upward. The liquid pumped upward consists of the bubble wakes and the liquid brought into the jet region by turbulent entrainment. The expansion of the gas bubbles as they rise through the liquid is taken into account. The continuity and momentum equations are solved numerically for an axisymmetric air jet submerged in water. Water pumping rates are obtained as a function of air flow rate and depth of submergence. Comparisons are made with limited experimental information in the literature.

NOMENCLATURE

a  local outer radius of liquid jet region
ac local radius of bubbly core region
K0  turbulent jet entrainment coefficient
 g  acceleration of gravity
K  ratio of bubble wake volume to bubble volume
L  depth of jet origin below liquid surface
M  mass flow rate
p  pressure
pa  atmospheric pressure
Q  volume flow rate
r  radial coordinate, origin is at jet axis
R  perfect gas constant
T  absolute temperature
u  velocity in x direction
um  terminal velocity of single bubble rising in infinite liquid region
v  velocity in radial direction
x  vertical coordinate along jet axis, origin is at gas release orifice
p  fluid density
s  surface tension
Subscripts:
c  jet core region
g  gas phase
i,o inside and outside of a particular jet region
l  liquid phase

INTRODUCTION

Liquid pumping can be obtained by utilizing the buoyant force of gas bubbles rising through the liquid as shown in fig. 1. This is a free convection type of process using two immiscible fluids that have a large difference in density (1) (2). Because of the large density difference made possible by using a gas and a liquid, large amounts of liquid pumping can be obtained. The large local density difference is in contrast to ordinary thermally driven single phase free convection where the density variations are usually small.

![Figure 1: Configuration of liquid jet induced by rising column of gas bubbles.](image-url)
An interesting application of bubble pumping is for ice prevention in lakes (3) (4) (5). Since the maximum density of water is at 4°C, the water in the bottom regions of a quiescent lake can be as much as 4°C warmer than the surface regions when the air temperature is below freezing. Ice formation on the lake can be diminished or prevented by pumping the warmer bottom water toward the surface by means of rising air bubbles. Bubble pumping is also used in fluidized beds, and for aeration in water purification and waste treatment plants. The flow induced by a curtain of rising air bubbles has also been considered as a breakwater for incoming water waves (1) (2).

The purpose of this paper is to formulate a two-phase model and analyze the turbulent liquid pumping by a rising discharges of gas bubbles. By means of the drag on the liquid, the buoyant force of the bubbles imparts an upward momentum to the liquid. There is turbulent entrainment of liquid into the rising jet as indicated in Fig. 1, and the result is that substantial vertical liquid pumping can result. The extent of the pumping is illustrated by experimental results in refs. (4) and (5) which show that for bubbles rising through 1.68 m (5.5 ft) of water, an air flow of 0.000472 m³/sec (1.68 ft³/sec) produced a pumped liquid volume 120 times that of the gas. In ref. (6) the volume of water pumped per unit volume of air for an orifice at a depth of 4.5 m (14.7 ft) varied from about 60 to 175 depending on the air flow rate. The analysis given here will provide the liquid pumping rate as a function of bubble rise distance and gas flow rate.

Experimental measurements of a rising water jet pumped by air were made by Kobus (6) at several air flow rates for an orifice depth of 4.5 m. A theory was given utilizing the experimentally measured flow to specify the entrainment term in the continuity equation. In ref. (7) an analysis was made of the bubble pumped jet in a manner analogous to a turbulent convective patch such as in ref. (6). This procedure leads to a singularity where the fluid velocity becomes infinite at the jet origin, making it necessary to define an apparent origin in order to compare the analytical results with experiment. The data of Kobus (6) was used in ref. (7) to determine the coefficients governing the flow such as the jet spreading rate and the turbulent entrainment coefficient. In order to obtain better agreement between the analysis and the experiment of Kobus, it was found necessary to decrease the entrainment coefficient substantially as the air flow decreased.

In ref. (8) analytical expressions are given from an approximate analysis by I. K. Konovol of the water pumped by air released from a submerged perforated pipe. The present situation is axisymmetric, whereas the perforated pipe provides a jet that is two dimensional in rectangular coordinates. The empirical constants in the theory were evaluated from laboratory observations for depths of the perforated pipe up to about 1 m and for air flow rates up to about 0.0015 m³/sec per meter of pipe length. Some limited full scale tests were also made at depths up to 10 m. Some data for a two-dimensional plane also given in ref. (6). The analysis here is concerned with localized discharges spaced apart along the length of a submerged pipe hence an axisymmetric jet is being considered rather than the perforated pipe.

The present work is an attempt to model the gas driven jet as a two-phase flow. A simplified two-phase model is constructed consisting of a bubbly core and an outer liquid flow. An entrainment model is constructed for the contributions to the entrainment by the outer liquid flow, the bubble wakes, and the rising gas bubbles.

**ANALYSIS**

**Model Description**

A glass tube having an opening about 1-1/2 mm in diameter was placed at the bottom of a tank 0.5 m deep and 0.31 m square in horizontal cross section. Motion pictures were made at several rates of air flow from the tube, and typical configurations of rising bubbles are shown in fig. 2.

Based on these observations, a model was constructed which was a compromise between mathematical difficulty and physical realism. In the model, as shown in fig. 3, the jet is considered axisymmetric with two regions. There is a central core surrounding the jet axis consisting of large bubbles rising in a chain bubble fashion and separated by liquid wakes that are carried along by the bubbles. Surrounding the core is an outer region of entrained

![Figure 2](image-url)

**Figure 2**. Air bubble rise patterns from 1-1/2 mm diameter orifice in water tank 0.5 m deep with 0.31 m square cross section obtained by T.Y. Hsu and N.N. McLellan.

1 Experimental results obtained with help of Dr. Y. Y. Hsu.
liquid being carried upward by the drag on the liquid arising from the buoyancy force of the bubbles. This model permits using different relations for the entrainment by the gas and by the liquid regions.

The flow field is assumed to be steady, isothermal and fully turbulent. The liquid density is assumed constant, but the gas density varies with the local pressure in accordance with the perfect gas law; thus the bubbles expand as they rise through the liquid. The bubbles are assumed to be sufficiently large that their drag is fully turbulent and hence they rise at a constant terminal velocity relative to the liquid. The local bubble velocity is assumed equal to the local liquid velocity plus the bubble terminal velocity. It is assumed that the gas leaves the orifice with negligible upward momentum. After the gas is released, there is an adjustable region within which the bubbles achieve their terminal velocity. For an installation in a lake or river this region would be small compared with the total rise height and hence this region is not taken into account.

As shown in fig. 1, the rising jet flow will turn at the liquid surface and move radially outward. At the surface the vertical velocity component has to go to zero. However, to incorporate this condition requires coupling the solutions for the jet and the turning zone which is a difficult analysis. The turning zone is not accounted for here; it is assumed that the jet continues from the surface as shown by the dotted extrapolation lines in fig. 1. Because of their strong vertical buoyancy force, the bubbles do not turn very much with the flow; hence they exert their pumping effect all the way to the surface. Also there is zero shear at the liquid surface which facilitates the turning and tends to minimize the influence of the turning zone in the rising plume. These same types of assumptions are discussed in ref. (10) for a free convection plume above a heated cylinder. Consequently an analysis without the effect of the turning zone should yield reasonable vertical pumping rates.

**Gas Continuity**

For a single rising bubble, let the ratio of the wake volume to the bubble volume be a quantity $K$.

From ref. (11), for bubble Reynolds numbers greater than about 200, which would be reasonable for the large bubbles in the present application, the $K$ is essentially constant and equals about 1.5. Then in the core region of local radius $a(x)$ in fig. 3, on the average $1/(K + 1)$ of the vertical height is occupied by gas bubbles and $K/(K + 1)$ is occupied by wake regions. This assumes for mathematical simplicity that the bubbles are rising in a chain-bubble fashion in which the bubbles are vertically spaced by the liquid wakes. Strictly speaking such a configuration exists only over a certain range of flow rates. However, the results from this model may apply to other bubble regimes. This is because, as discussed later, the turbulent entrainment of liquid by gas is minor compared with the entrainment by liquid. This tends to diminish the importance of the exact configuration of the rising gas. Since the gas weight flow rate is constant,

$$
M_g = \int_0^a \frac{\pi r^2}{K + 1} \rho_0 u \, dr = \text{constant}
$$

**Perfect Gas Law**

The pressure at height $x$ above the nozzle is $\rho_0 (L - x)$. Then from the perfect gas law the gas density at $x$ is

$$
\rho_g = \frac{1}{RT} \left[ \rho_a + \rho_0 (L - x) \right]
$$

where $P_a$ is atmospheric pressure at the liquid surface.

**Liquid Continuity**

The liquid continuity equation accounts for the liquid carried into the jet by turbulent entrainment. The entrained liquid goes into the liquid region surrounding the core, or into the bubble wakes which are growing as the rising bubbles expand,

$$
\frac{d}{dx} \left[ \frac{K}{K + 1} \int_0^c \int_0^x 2\pi r_p u_r \, dr + \int_c^x \int_0^x 2\pi r_p u_r \, dr \right] = -2\pi \rho_0 \Gamma_r x
$$

The term on the right will be expressed later in terms of a turbulent entrainment relation.

**Gas and Liquid Momentum**

In most applications involving air driven jets, the surrounding body of water is large; hence for simplicity in the present analysis, the surrounding liquid region will be assumed infinite. The analysis of a jet in a small container would be much more complicated because of liquid recirculation and the interaction with the container walls.

The upward buoyancy force of the bubbles produces a change in momentum (usually quite small) of the gas bubbles, a momentum change of the liquid in the bubble wakes, and a momentum change of the liquid in the region surrounding the bubbly core. This yields the momentum equation as

$$
\int_0^a \frac{g}{K + 1} (c_1 - c_2) \pi r_p \, dr + \frac{d}{dx} \int_0^c \frac{1}{K + 1} \int_0^x 2\pi r_p u_r \, dr
$$

$$
+ \left[ \int_0^a \frac{K}{K + 1} \int_0^x 2\pi r_p u_r \, dr + \int_c^x \int_0^x 2\pi r_p u_r \, dr \right]
$$
"Top Hat" Distributions

To integrate eqs. (1), (3), and (4), "top hat" velocity profiles are assumed which have yielded good results for free convection plumes (6),

\[ u_g(x, r) = \begin{cases} u_0(x) & 0 \leq r \leq a_0(x) \\ u_1(x) & r \leq a(x) \end{cases} \]

(5a)

\[ u_1(x, r) = \begin{cases} u_1(x) & a_0(x) < r \leq a(x) \\ 0 & a(x) < r \end{cases} \]

(5b)

The \( u_g \) and \( u_1 \) are related by

\[ u_g(x) = u_1(x) + u_w \]

(6)

where \( u_w \) is the terminal velocity of a single bubble rising in a large region of quiescent liquid.

Insert eq. (5) into eqs. (1), (3), and (4) to obtain

\[ \frac{\pi \rho_0}{K + 1} \frac{d}{dx} \left( \frac{a^2 - a_0^2}{u} \right) = -\left(2\pi \rho_1 \nu \right)_{\text{right}} \]

(7)

\[ \frac{\pi \rho_0}{K + 1} \frac{d}{dx} \left( \frac{a^2 - a_0^2}{u} \right) + \frac{\pi}{K + 1} \frac{d}{dx} \left( \frac{a_0^2 - a^2}{u} \right) = \frac{\pi \rho_1}{K + 1} \left( \frac{a_0}{a} \right)^2 \]

(8)

(9)

Entrainment Function

An expression is now needed for the entrainment on the right side of eq. (8). As discussed by Morton (12) for free convection plumes above fires, for a buoyant single-phase jet the entrainment depends on an additional variable which is the density in the plume relative to the density of the surrounding fluid. The entrainment is reduced when the plume density is smaller than the density of the surrounding fluid. The present situation involves two distinct phases that each maintain their separate identities; hence there will be two types of entrainment, liquid-liquid and gas-liquid. For the latter there is a lack of entrainment information when the density ratio is as small as that for air to water. As soon as some liquid is in motion, much of the entrainment is by liquid entraining additional liquid which is reasonably well understood.

It was deduced in ref. (12) by using the information in ref. (13), that for a single phase jet the usual jet entrainment coefficient \( E \) used when the jet and outer fluid have the same density, should be modified when the jet and outer fluid densities are different. The \( E \) is multiplied by the density ratio \( \left( \rho_0/\rho_1 \right)^{1/2} \) where \( \rho_1 \) is the density in the jet and \( \rho_0 \) is outside the jet. For the present situation the liquid-liquid entrainment terms will therefore have a unity ratio factor, while the gas-liquid terms will contain \( \left( \rho_0/\rho_1 \right)^{1/2} \). Since the entrainment is so different for the two phases, the two-phase nature of the jet will be retained rather than trying to assign an average density to the entire jet.

The entrainment also depends on the velocity of the jet relative to its surroundings, and on the interfacial area between the jet and the surrounding region. These velocities and areas are different for the gas and liquid portions. The liquid region moving at velocity \( u_b \) as shown in fig. 3, entrains liquid from the quiescent fluid around it. The higher velocity bubbly region is moving at velocity \( u_w \) relative to its surrounding liquid, and hence should enhance the entrainment process. A well defined interfacial area bounding the bubbly region can only be obtained by utilizing a simplified model such as in fig. 3, and this area is used to obtain the magnitude of the entrainment. However, if this entrainment were assumed to be retained in the core, the core would then become a liquid jet containing a bubbly core and the difficulty of defining the entrainment for this two-phase inner jet would become the same as that for the original two-phase problem. Although the concept of a bubbly core is used to provide a well defined interfacial area, it is realized that the bubbly motion is actually more random. With these considerations in mind and in the absence of any better information on such a two-stage entrainment process, it is assumed that the vigorous action of the bubbly region increases the turbulence in the liquid surrounding the bubbles and thereby enhances the total entrainment into the moving region. This is in accord with the results in ref. (15) that the entrainment is a function of the excess momentum flux in the jet. Thus in the present model, as the jet grows with increasing height above the source of gas the core will retain its identity as being composed of only bubbles and their wakes. Hence the total entrainment will be taken as the entrainment by the moving liquid outside the bubbly core, augmented by the entrainment effects of the liquid wakes and gas within \( u_w \) core, and is given by

\[ \left(2\pi \rho_1 \nu \right) \text{right} = 2\pi \rho_0 \frac{d}{dx} \left( \frac{a^2 - a_0^2}{u} \right)_{\text{right}} + \frac{2\pi \rho_0 \rho_1}{K + 1} \left( \frac{a_0}{a} \right)^{1/2} u_w \]

(10)

Solution for \( u_b \) and \( \rho_0 \)

To obtain the amount of liquid being pumped by the rising gas, the liquid velocity of jet radius must be obtained. The liquid mass flow rate in the wake regions is known from the specified gas flow rate as \( \rho_0 \left( u_0/\rho_0 \right) \). The mass flow rate of liquid is then

\[ \sum \rho_0 \left( u_0/\rho_0 \right) = \pi \left( a^2 - a_0^2 \right)_0 u_0 + \frac{K \rho_0}{1 + K} u_w \]

(11)

Since \( M_g \) in eq. (7) is a constant, eqs. (8) and (9) can be simplified by using eq. (7) to eliminate some of the \( u_g \). Eq. (10) is then substituted for the right side of eq. (8). The result is

\[ \frac{K \rho_0}{1 + K} u_w \]

(12)
The $u_w$ can be eliminated in terms of $u_3$ by using eq. (6), and the $q_{0e}$ is given in terms of $x$ by eq. (2). From eq. (7) the $a_w$ can then be eliminated in terms of $u_w$ and $x$. Thus eqs. (12) and (13) are reduced to equations for the unknown $u_w(x)$ and $a(x)$. To obtain numerical results the differentiations were carried out analytically and then the equations combined to eliminate $du_w/dx$ or $da/dx$. The result was the following set of simultaneous differential equations that were solved by the Runge-Kutta method (14),

$$
\frac{du_w}{dx} = \left[ 2\rho_k u_{w} \left( \frac{\rho_0 u_{w}}{\rho_k} + \left( \frac{\rho_0}{\rho_k} \right) (K + 1) u_{w} + \frac{u_{w}}{K + 1} \right) \right]^{1/2} \left[ \frac{K + 1}{\rho_0 (K + 1) u_{w}} \right]^{1/2} \left( \frac{K + 1}{\rho_0 (K + 1) u_{w}} \right)
$$

$$
\frac{da}{dx} = \left( \frac{u_{w}}{u_3} \right) \frac{a + (K + 1) u_{w} u_{w}}{2a_0 \rho_k (u_{w} + \frac{u_{w}}{K + 1})} \left( \frac{K + 1}{\rho_0 (K + 1) u_{w}} \right)^{1/2} \left( \frac{K + 1}{\rho_0 (K + 1) u_{w}} \right)
$$

At $x = 0$, $a = a_0$, and $u_w = 0$. Then the initial conditions at $x = 0$ to begin the integration are from eq. (7),

$$
a(x = 0) = \left( \frac{M (1 + K)}{[\mu_b (p + d_0 L)]} \right)^{1/2}
$$

and $u_w(0) = 0$. The latter condition however causes starting difficulty in the integration since it is in the denominator of a few terms, so a small value was used, $u_w(0) = 0.001$. The calculations were tested using smaller $u_w(0)$ and no significant changes were found.

**DISCUSSION**

As shown by fig. 4 the liquid pumped to the surface increases with the depth of the orifice below the surface and with the gas flow rate. For a fixed weight flow rate, the volume of gas introduced at the orifice decreases as the orifice depth increases. Hence it seems better to present the results in terms of gas weight flow rate than in terms of volume flow. For each orifice depth the results in fig. 4 lie fairly well along a straight line on a log-log plot. The slope decreases somewhat as $L$ is increased but the results vary essentially as $M = M^3$. A cross plot of the results shows that for a given $N$, the $M$ variation with $L$ is also as a power function.
When $M_1$ and $M_2$ are in kg/sec and $L$ is in m, then $C = 365$ for $E_o = 0.08$ and $C = 550$ for $E_o = 0.116$. When $M_1$ and $M_2$ are in #/sec and $L$ is in ft, then $C = 111$ for $E_o = 0.08$ and $C = 172$ for $E_o = 0.116$.

To examine in more detail the effect of the various entrainment terms in eq. (10) calculations were made with either the liquid wake term and/or the gas

$$M_1 = C M_1^{1/4}$$

(17)

$$M_2 = C M_2^{1/4}$$

$$M = C M^{1/4}$$

When $M_1$ and $M_2$ are in kg/sec and $L$ is in m, then $C = 365$ for $E_o = 0.08$ and $C = 550$ for $E_o = 0.116$. When $M_1$ and $M_2$ are in #/sec and $L$ is in ft, then $C = 111$ for $E_o = 0.08$ and $C = 172$ for $E_o = 0.116$.

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entainment term omitted. As might be expected because of the small value of the entrainment term, the gaseous liquid mass effect had less than a 15% effect on the pumped liquid mass. The liquid wake term had a significant effect for small x, where the total liquid flow is small, as it helped initiate the entrainment process. The effect of this term decreased as the total entrained flow became more substantial. For a depth of 1.524 m (5 ft) this term increased the flow in the range of 10 to 75% as the gas flow ranged from the smallest to the largest values on fig. 4. For a depth of 9.144 m (30 ft) the wake term contributed about 5% to the pumped flow for any gas flow rate.

The liquid wake term on the left side of eq. (9) is an especially important feature of the present analysis. For small x it provides inertia within the flow when the total entrained liquid is still small and produces a buoyant force from producing unrealistically high liquid velocities near the origin of the numerical calculations.

The bubble pumping process provides a fluctuating flow so that experimental measurements are difficult. Some comparisons will now be made with the small amount of data available in the literature. These results will serve to emphasize that although there is still appreciable uncertainty in the amount of flow being pumped, the trends with depth and gas flow rate have been approximately established. The most striking feature is that the ratio of pumped liquid volume to gas volume is quite large.

In fig. 13 of ref. (6) Koubis gives the ratio of pumped liquid volume to the gas flow rate for various gas flow rates. There is a set of data for the local flow rate at a location 3.5 m above an orifice 0.5 m deep. These local flow rates were also obtained from the present computer calculations and a comparison is made in table I. For 

\[ E_o = 0.8 \]

the present theory predicts a flow that is somewhat low at the high gas flow rates and somewhat high at the low flow rates. For 

\[ E_o = 0.116 \]

the agreement is good at the high air flow rates. Before further discussion the results of ref. (4) should be included.

The following correlation is given from available data in terms of volume flow rates of air and water and depth of submergence (in ref. (5) the exponent on \( Q_g \) is 1/2).

\[ Q_w = Q_g \cdot \rho \cdot g \cdot \Delta \]  

where \( Q_w \) and \( Q_g \) are in m³/sec and \( L \) is in meters.

Because of the difference in geometry precise comparisons cannot be made, but it is interesting to see how the predictions of liquid volume pumped per unit gas volume \( Q_v/Q_g \) compare for the release from an orifice as obtained from eq. (17), and from a meter length of perforated pipe, eq. (15). Results are given in table II and it is seen that the pumping rates are of the same magnitude. The \( Q_v \) was assumed to be at the discharge location, although this was not clearly specified in the reference.

In ref. (6) it is mentioned that the bubbly region of the axiymmetric jet is approximately contained within a cone having a total included angle of 12°. Although the present mathematical model considers all the gas to be in the form of large bubbles contained in the core of the jet, in the physical case there are small bubbles that break off from the large ones as shown in fig. 2. The turbulent motion diffuses the small bubbles within the flow so that they probably extend throughout most of the entrained region. Hence the total bubbly region should give an indication of the extent of the jet region. Using a total included cone angle of 12°, the jet radius at the surface is

\[ a = k = L \tan \theta = 0.105 L \]  

The photographs in fig. 2 indicate an increase of cone angle with gas flow rate. In fig. 2(a) the cone angle is about 14°, while in fig. 2(d) it is about 19°.

Equation (20) is plotted in fig. 7 and compares reasonably well with calculated results for an entrainment coefficient of \( E_o = 0.08 \). For a larger total included angle of say 18°, which is characteristic of figs. 2(c) and (d), eq. (20) becomes \( a(L) = 0.158 L \). As shown by fig. 7, this provides reasonable agreement with the values computed with \( E_o = 0.116 \).

CONCLUSIONS

A tractable mathematical model was formulated for computing the liquid carried upward in an axiymmetric jet driven by a rising stream of gas bubbles. The model geometry was based on observations of air rising through water 0.6 m deep. Liquid is carried into the jet by turbulent entrainment and a difficulty in the analysis is in specifying the proper value of the entrainment coefficient. Calculations were made for two values of the entrainment coefficient within the range given in the literature. The large buoyancy resulting from the large density difference between water and liquid produced considerable liquid movement compared...

Table I: Volumetric Cooling Rates in an Axisymmetric Jet at a Location 3.5 m above Outlet Surface

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Cooling Rate (kcal/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2.4</td>
</tr>
<tr>
<td>200</td>
<td>5.2</td>
</tr>
<tr>
<td>300</td>
<td>8.0</td>
</tr>
<tr>
<td>400</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Table II: Volumetric Heating Rates for Kohn's Air Flow

<table>
<thead>
<tr>
<th>Kohn's Air Flow</th>
<th>Volume Rate (kcal/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0004</td>
<td>175</td>
</tr>
<tr>
<td>0.0006</td>
<td>346</td>
</tr>
<tr>
<td>0.0008</td>
<td>527</td>
</tr>
<tr>
<td>0.0010</td>
<td>708</td>
</tr>
</tbody>
</table>

Table III: Volumetric Cooling Rates for Kohn's Air Flow

<table>
<thead>
<tr>
<th>Kohn's Air Flow</th>
<th>Volume Rate (kcal/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0004</td>
<td>217</td>
</tr>
<tr>
<td>0.0006</td>
<td>317</td>
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<tr>
<td>0.0008</td>
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<tr>
<td>0.0010</td>
<td>517</td>
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