Image processing applied to characterize the denser gravity current propagates over rigid surface into lighter fluid

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Abstract An image processing applied to the series of laboratory experiments of gravity current in order to obtain the two dimensional propagation of denser fluid (saline water) with density ρ+Δρ injected over a horizontal bottom of a basin containing a static lighter fluid (fresh water) with density ρ. The gravity current was colored and the images sequences can have a variation of light intensity where the dark regions represents the gravity current in the case of motion and white region represents the static fluids. Two dimensional profiles of the gravity current showed that the flow is non-axisymmetric and the evolution of the front position showed a power law with time.

Keywords: Gravity currents, Flow regimes, Images processing, scaling law.

Introduction

Gravity currents are flows driven by density differences between two contacting fluids resulting from temperature gradients, dissolved substances or solid particles in suspension [1, 2]. The release of pollutants into rivers, oil spillage on the sea environment and desalination plant outflows are a few of man-made gravity currents that occur in water masses and frequently cause negative environmental impacts because these problems arise in the disposal of geothermal brines and wastes from mining operations and another industrial processes, which are heavier than ambient. Examples of gravity currents occurring spontaneously in nature are the sea-breeze and oceanic fronts, underwater debris flows and turbidity currents. The first of the theoretical work on gravity currents are calculated by von Kármán [3] up to that by Benjamin [4].

Since the 1950s, the gravity currents have been studied extensively in laboratory experiments. In a two dimensional shallow-water model, Huppert [5] builds a similarity solution to the governing nonlinear partial differential equations which describe the shape and rate of propagation of the gravity current. Huppert's theoretical results are in good concordance with the experimental results obtained by Britter [6] in the case of an axisymmetric spreading of salty water into fresh water. Didden & Maxworthy [7] calculated the progress and the plunging of a gravity current using the equilibrium between the inertia and the gravity forces in the inertial regime and between the viscous and the gravity forces in the viscous regime, the progress of a gravity current has the following form: $L \sim (g'Q)^{1/3} t^{(\alpha+2)/3}$ where g' is the apparent acceleration of gravity current at the source and Q is the initial at the source specific fluxes of mass in the two-dimensional for inertial regime. In the viscous regime, the law writes: $L \sim (g' Q^3/\upsilon)^{1/5}\, t^{(3\alpha+1)/5}$ where $\boldsymbol{\upsilon}$ is the kinematic viscosity in the two-dimensional case. If the gravity current propagates on the bottom of a basin, the progress flow the following law:$L \sim (g' Q^3/\upsilon)^{1/5} t^{1/5}$.

Huppert and Simpson [8] described the gravity current of a denser fluid inside a lighter fluid over a rigid plane when the ambient fluid is viscous and at rest. Huppert and Simpson defined three regimes: (i) the slumping regime, (ii) the inertial regime and (iii) the viscous regime. Most of the studies have focused on the characteristics of the injection zone but few have fully considered the inflow after the interaction of injected brine fluid with (free surface, interface, and bottom).Sharp [9, 10] studied the spreading caused by a steady source of dense fluid. The outer boundary of the gravity (density) current will always change with time, when the bottom is horizontal and the ambient is calm. The radial spreading on a horizontal boundary was firstly approached by who presented plots fort the estimation of the dimensionless distance from the impingement point to the front of the density current, as a function of a dimensionless discharge flow rate and a dimensionless time.

Most of the studies have used the front position x=f (t), a parameter that is easy to measure, to test their theories. On the other hand, the measurement of the appropriate height of the current to calculate the Froude number is difficult because real currents exhibit a deeper head than the following fluid, and mixing between dense and ambient fluids prevents the determination of a well-defined boundary. The height profile of the current is irregular and unsteady [11]. The field of time-dependent homogeneous objectively driven gravity flow studied of Rottman and Simpson [12] on instantaneous fixed-volume releases in plane geometry for bottom gravity flows in the absence of topography. D'Alessio *et al*. [13] employed a two-layer shallow-water model to study sudden releases for fixed volumes entering a lighter ambient fluid as a bottom gravity flow. The discharge with small Reynolds number from conclusion by [5, 7] or after important time from the initiation of spreading [6, 14, 15].

The present study aims to applied the image analysis on the laboratory experiments to explored the gravity currents in two dimensional flow of salt water (denser fluid) into a calm fresh water (lighter fluid). The outer boundary of the gravity current and positions (distances) of x and y from the injection point determined and relation with time ($x{\sim}t^B \; and \; y{\sim}t^D$) under the influence of initial or the local jet flow parameters.

Experimental setup and procedure

1-Setup

The basin has a length of 1.0 m with rectangular cross-section, 0.38 m wide and 0.42 m deep and white plastic bottom, as represented in Fig.1.The walls are made of 5mm transparent glass, containing the static ambient liquid of 20L at 0.05m allowing the visualization of the gravity current development; the basin bed is smooth and is kept horizontal for the duration of all the experiments. A reservoir of 60L was utilized as the source of salty water with a valve for controlling the releases of the gravity currents which transit into the flowmeter. An injection tube released the flow at the horizontal bottom surface (5mm diameter of the tube) manufactured in transparent plastic and which links the reservoir to the basin.

2-Measurement techniques

The viscosity of the salty water was measured against the concentration using an Ostwald viscometer. In our experiments used the concentration of salty water is 40g/L and measured the salinity, which with together conductivity for freshwater and salty water, and temperature used the calibrated conductivity meter. A Techfluid 2150 flowmeter aiming at controlling and measuring the flow rate of the gravity current as it is released from the reservoir of salty water into the basin. The characteristic initial injection velocity u_o $u_o = Q_o/(\pi/4 \,.\, D^2)$ was determined by dividing the measured flow rate by the cross section area of injection tube.

A light source made of 50 Hz- 500w projector lamp was placed in front of basin. The experiments were conducted in the dark laboratory room to avoid other light sources disturbing the experiments (Fig.1). A small red soluble dye quantity of Rhodamine B was used as tracer in order to visualize the flow of gravity current (salty water) in the reservoir and its agent is introduced for video-photographic analysis purpose. The ambient liquid at rest is fresh water in the basin. The dye was not effect to the density of salty water and viscosity. For each experiment a video sequence with the frequency of 38 frames per second, an observation system consisting of one camera was used camera (type: Photron Fastcam) and it can take 190 images per second with a resolution of (1024x1024 Pixels). The camera was placed 1m above to water surface of basin. The pictures observed by this the camera is simultaneously captured at a frequency of (38 Hz) owing to a system of image capturing and which consists of a PC equipped with a Pentium IV processor (2.6 GHz) of 1024 Mb of random-access memory .

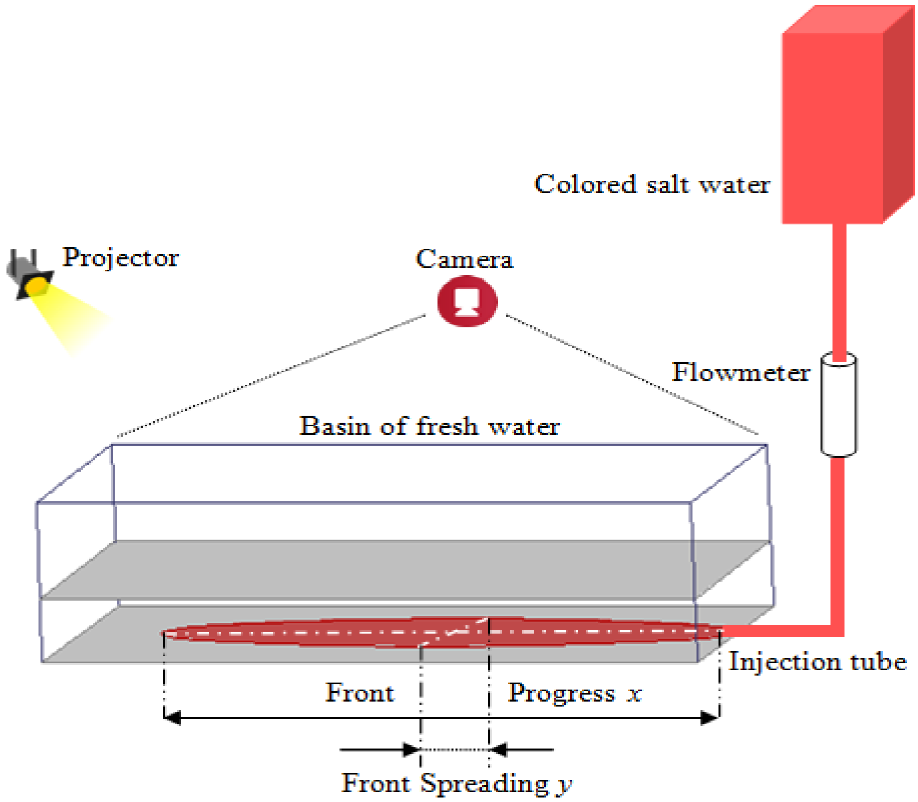

Fig.1.experimental Setup

3-Experimental procedure

The present work is performed with 6 experiments, and flow rate was repeated 3 times to check the reproducibility of experiments. The flow rate of gravity current is varied from 20 L/h to 70 L/h with increment of 10 L/h. The reduced gravity and viscosity are fixed respectively at g' and υ are 0.38 m/s², and 10^{-6} m²/s. The propagation of gravity current of denser fluid represented by a saline water with density ρ+Δρ equal 1040 kg/m³ injected in the bottom of a basin containing a static lighter fluid represented by a fresh water with density ρ equal 1000 kg/m³. Having the same source condition in all series and the temperature ranging from 19 to 24 °C.

The control parameters of experiments

The horizontal propagation of denser fluid region is due to the initial momentum flux $M_o = Q_o U_o$, where indicates the initial salt water injection velocity, $Q_o = U_o . \frac{\pi}{4} . D^2$ the initial inflow and D represented the diameter of injected tube, the flow of denser fluid into bottom deep lighter fluid formed immersed bulk due to the buoyancy flux ($B_o = g' . Q_o$, $g' = \frac{\Delta\rho}{\rho} . g$, where $g'$is initial visual acceleration of gravity at the injection source, g is acceleration due to gravity, $\Delta\rho$ denotes the difference densities between salty and ambient fresh water, ρ the uniform fresh water density). Therefore, the initial (at the jet exit) parameters Q_o, M_o, B_o, g' are used for flow analysis with a possible dependence on the densimetric Froude number Fr_o and Reynolds number Re.the previous two parameters used to characterize different flow regimes. The range of initial injection densimetric Froude numbers Fr_o from 6.5 to 22.8 was studied and the flow was transmitted progressively from laminar to the turbulent, with the Reynolds number Re_o from 1415 to 4951.

Image processing analysis

Controlled quantity of red dye Rhodamine B for obtained the images have a variation of light intensity which are the darkness regions represents the gravity current in the case of motion and white region represents the static fluids. The instant of the first introduce injection on the bottom of the basin from the video sequence of all the experiments is considered as the time equal zero until it before reaching to the walls of the basin for the analysis of propagation and spreading gravity current on the smooth bottom. Firstly take the image at time equal zero without any motion, then it analyzed with images sequences by the difference process that means$(I - I_o)$. To discriminate the noise in images we have used a filletring based on FFT and the filtered images are binarized with an adaptive threshold in order to determine the spatiotemporal interface position of the gravity current as shown in Fig.2, and Fig.3.After to complete the characterization of the flow, we used the space-time diagram technique.

The two techniques of image processing are complementary to characterize well experimentally the flow of gravity current in our work. The two dimensions profiles of the gravity current showed that the flow is non-axisymmetric. The evolution of the front position showed a power law with time, and a horizontal bottom coordinate system x-y according to Fig.4. An image analysis applied to investigate the gravity currents developing over a horizontal bottom and smooth rigid surface of the basin. Immediately after the injection of dense fluid inside the basin, a gravity current of heavy fluid forms after a period of time and yet the injection zone depending on the flow rate.

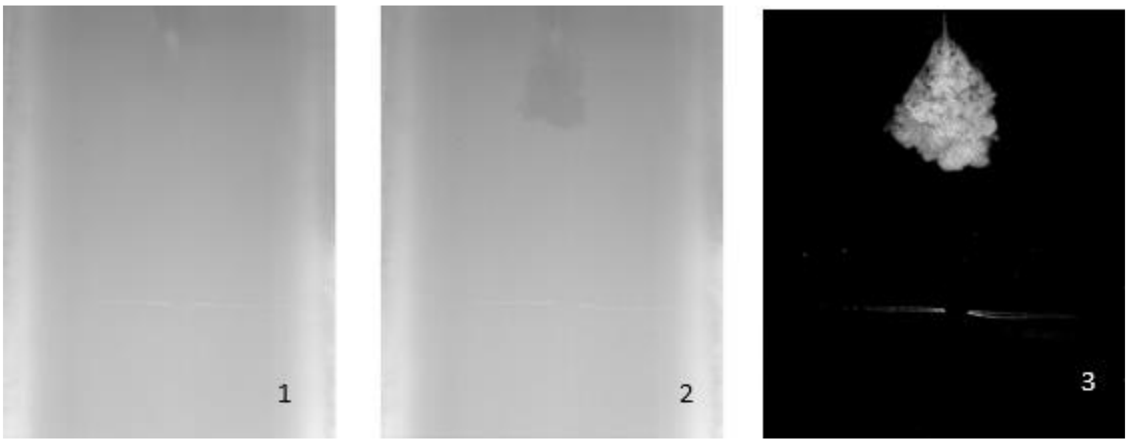

Fig.2. represents steps of the images sequences analysis; (1) Image number zero at t=0, (2) As an example of one of the images from images sequences at t=1.41s, and (3) The images after applied the difference process and FFT at t=5.37s.

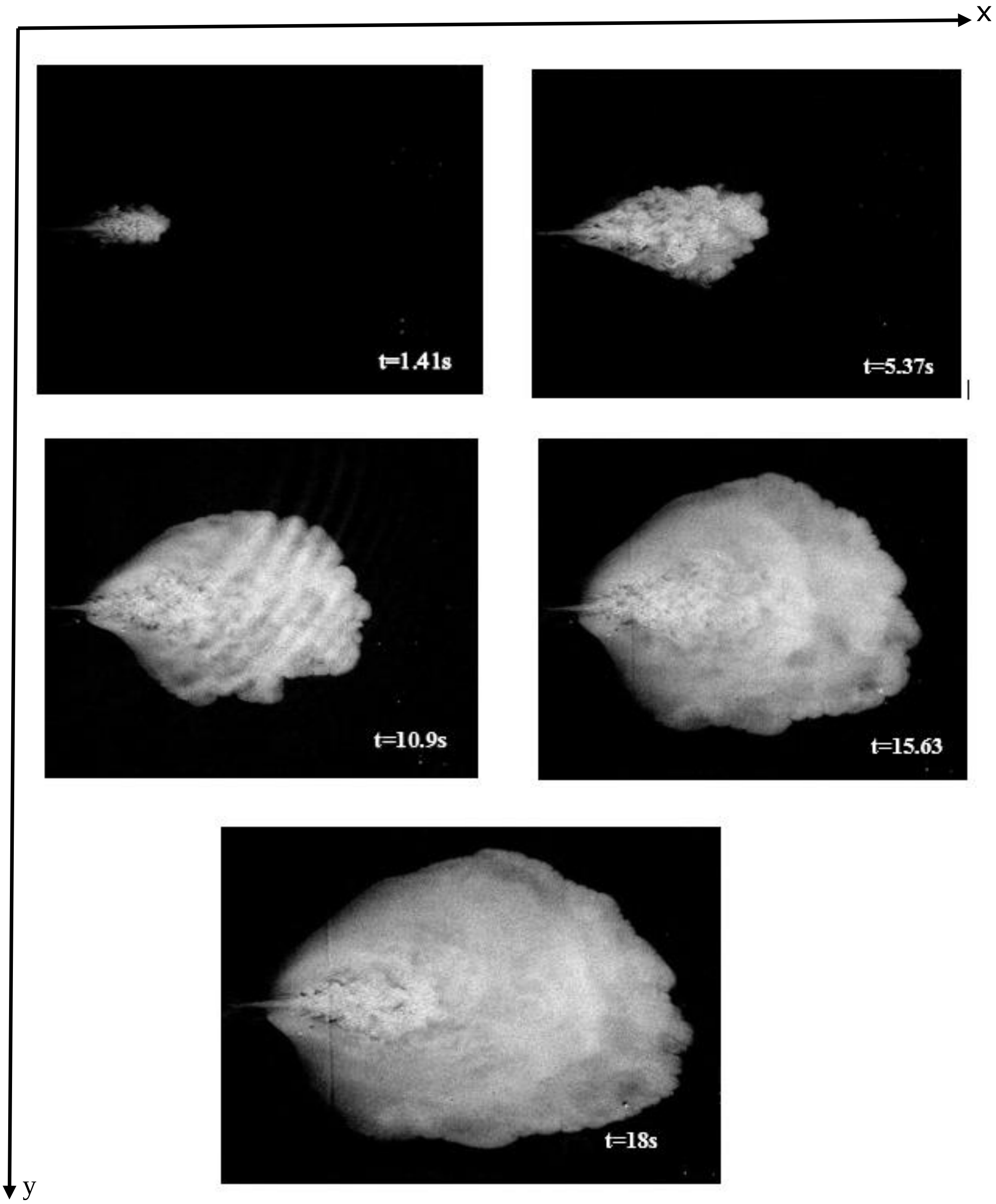

Fig.3. The snapshot of gravity current obtained from real image with initial image at t=o

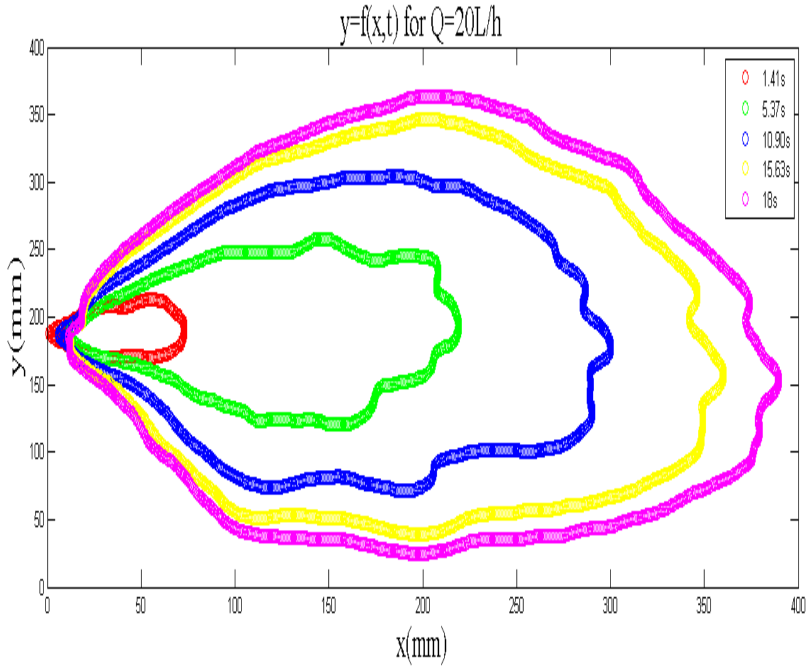

Fig.4. The profile of gravity currents outer boundary *y=f(x, t)*.

Results

The change in shape of gravity currents for every flow rate depends on the quantity (volume) of salt water injection that it leads to the variation in the angles values of stream injection for every flow rate affecting on the final gravity current shape (for small times which is represented the beginning of the injection flow, so the limits of angles between 30°-40°), also taking into consideration the time periods to configuration the gravity currents varies due to differences in velocities. During the interval of time, the gravity current travels with constant velocity, depending on the initial height and modified acceleration due to gravity.

Observation of the flow structures in a fully developed gravity current front were done by repeating experiments. The average of the gravity currents heads from along the center of the injection tube at the moment of each final frame is very small of every flow rate are 0.43, 0.55, 0.56, 0.63, 0.69, 0.75mm respectively , only when it is enter and then starts wane to form the thickness of layer gravity currents propagating over bottom rigid horizontal surface. These experiments, however, served to emphasize the importance of including the effect of the ambient fluid on the gravity current when the current initially occupies a small fraction of the total depth. On the other hand the variation in the gravity current gives it difficult to decide the description dependence on small height for determining the Froude number.

The experimental results are discussed in the framework of Huppert theory [5], the front of the two dimensional gravity currents due to a constant inflow salt water into fresh water. Through used the scaling law by applied the power fitting for measurements the exponent $B \ and \ D$, $x = At^B$, $y = Ct^D$ in a series of all experiments will get the functional forms the positions x and y together with time relationships and estimated the .The observed variation of distances with time as approximately $x{\sim}t^{0.45}$, and $y{\sim}t^{0.65}$ it was found that the B and D did not vary noticeably within each experiment, its value being $B = 0.45 \pm 0.04$ and $D = 0.65 \pm 0.06$.This leads to study the propagation and spreading is changeable problem since the gravity current grows with time and the outer boundary variations as shown in table1. As seen, the shape of the outer boundaries of the gravity currents are nearly elliptical form as in Fig. 4.

The different experiments which are represented by series of frames were used to determine the relations between the front progresses in x-axis, and the front spreading in y-axis, with the time evolution of the visual outer boundary and obtain on the shape of the gravity current front.

Q(L/h)	Progress Law Of program x=f(t)	Progress Law manual x=f(t)	Spreading Law of program y=f(t)	Spreading Law Manual y=f(t)	Time(s)
20	$x = 108.5t^{0.49}$	$x = 110t^{0.48}$	$y = 46t^{0.71}$	$y = 50t^{0.70}$	$0.16<t(s)<20.64$
30	$x=128.8x^{0.47}$	$x = 133t^{0.46}$	$y=54.7t^{0.69}$	$y =53\ t^{0.69}$	$0.13<t(s)<15.9$
40	$x=144.5t^{0.46}$	$x = 149t^{0.45}$	$y=56.3t^{0.67}$	$y= 59.5t^{0.66}$	$0.1<t(s)<14.7$
50	$x=163.4t^{0.45}$	$x = 166t^{0.44}$	$y=66.4t^{0.64}$	$y = 64.2t^{0.66}$	$0.1<t(s)<14.5$
60	$x =181.2t^{0.43}$	$x = 183.3t^{0.42}$	$y =76.3t^{0.62}$	$y= 75.2t^{0.64}$	$0.1<t(s)<13.3$
70	$x = 204.4t^{0.42}$	$x = 202.9t^{0.41}$	$y = 84.3t^{0.59}$	$y = 81.6t^{0.61}$	$0.08<t(s)<10.9$

Table1 The programing and manual scaling laws for two dimension gravity currents.

Conclusions

The image processing technique used in this work is easy way based on light intensity to assess the immediate propagation and spreading of gravity currents. This ImageJ software provides the resulting gravity currents profiles are useful data for obtained the front positions in direction of x and y. In this case the flow is effectively two dimensional, for every experiment is shown to illustrate the application of image processing that allows build a relationship between time and fronts of progress and spreads.

It is clear from Fig.3 and Fig.4 respectively, the representation of the variation of time with x and y this means herein the outer boundary of gravity currents, then the difference process used for explain the fully formation of gravity currents and every image was clarified the instant of each gravity current position.

As shown the table.1 see the alteration of flow regimes was in viscous regime $x{\sim}t^{1/2}$ this confirmed experimentally by Britter [6]. The flow spreads and progress in 2D in a forward of injection source point as a gravity current, that means the dense fluid layer propagated horizontally on the bottom of lighter fluid at the basin.

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