UNDER PEER REVIEW

Propagation Speed of the Frontal Head Through Lock-Exchange Density Current in Cold Fresh Water: Simulations without the Effect of Back-reflected Waves.

Abstract

The behaviour of warm water discharged at $4°C$ through lock-exchange in cold fresh water was investigated numerically. Simulations were conducted using $Fr = 1$, $Pr = 11$, and varying Re between 50 and 100, fixing lock-volume at the centre of the domain. This investigation as presented here is practical and can also enhance policy making towards the protection of the aquatic ecosystems. The aim of this investigation is to better fathom and as well, gain more insight into such flows. Our results have shown a speedy movement of the lock volume at the centre of the domain with a leading head at two front on the floor which resulted in a hat shape within the first few time frame. Result showed that lock volume collapsed uniformly before splitting into two equal halves and began to form density current. Fluid movement in the second phase is independent of the back reflected waves. We were able to identify two regimes of flow with a stepwise decreasing velocity in the second phase. Our results have shown that velocity with which the current travels with in the second regime is higher within the first time frame as compared to those by [3, 9, 23] with the effect of back reflected waves (see Fig. 4(a), 5(a). One major factor that is responsible for decrease in the velocity here is mixing. Because mixture here requires a very little mixing before it attain the same density with the ambient fluid. Previous results have also shown that the front velocities in the collapsing phase are independent of lock volume [9]. But this seem not to be the same here because fluid movement in the first phase (regime) is not totally independent of the lock volume [23] and its position here, where density difference is as a result of temperature. However, our scaling power laws here is the second phase show some variations with previous studies by [3, 23] where we have effect of back reflected waves. But results in the collapsing phase here are in strong agreement with those in the first phase of our previous simulations with small lock volume [23]. Generally, the spreading behaviour here is dependent on lock volume, barrier position, density difference and Reynolds number.

Keywords: Density current, Cabbeling, Regimes of flow, Temperature of maximum density.

1 Introduction

Gravity current flows are practical cases that are frequently encountered in nature and also in some man-made situations. These currents are mainly driven by density differences (i.e., whenever flow fluids of different densities come in contact then, the lighter fluid will over-ride the denser fluid forming gravity currents. Fluid motion in such cases are usually in the horizontal direction) [1, 2, 3]. In most of the experimental and numerical studies, this density differences is usually by change in temperature, salinity or concentration of suspended particles [4]. Gravity currents in nature sometimes become evident when water in some estuaries, lakes, etc. come in contact. Being that some of the water in these estuaries, lakes, etc., are saltier or colder, this in turn will form density current as lighter fluid flow to the surface. In some cases, the water in such areas also contains more suspended sediment than the surrounding water [3, 4] . Furthermore, when the door of a heated room is opened for ventilation, it can be observed that cold air from outside flows into the room, displacing the less dense warm air on the floor [1]. These currents can also be found in thunderstorm outflows, sea-breeze fronts, discharge of industrial waste water into rivers, lakes or oceans, volcanic clouds, etc., [1, 2, 3, 4, 5, 6, 7].
It is believed that apart from the behaviours as recorded by the various authors, it is also possible that the most important practical aspect of this phenomenal flow is the determination of the rate of advancement of the frontal head. Indeed this was the stated aim of the first theoretical calculation, by von Karman (1940) as also recorded in the literature by [8]. Quite a number of literature have also been given in this area of research and also examined theoretically, experimentally and numerically together with some mathematical relations and values that describes the propagation speed and spreading distance of these currents. Different regimes of flow are also identified that describe the flow behaviour [2, 3, 9, 10]. Research has also shown that gravity currents usually undergo either two or three distinct phases of flow and these include: a slumping phase, self-similar phase and viscous phase [8, 11, 12]. As also recorded in the literature of [2, 3, 8, 12, 13] that after the instantaneous removal of the gate, an initial adjustment phase where the advancing head varies with approximately constant velocity. Followed immediately by the second phase after the ambient fluid had reflected at the rear wall, it in turn overtake the penetrating head of the current. If only the lock-exchange experiment was carried out in a finite confined channel [2]. At this point in the flow, the penetrating head advances as $t^{2/3}$, but decreases with front speed as $t^{-1/3}$, where t is the time after which the gate was removed. Lastly, is the phase where viscous effects overcome inertial effects and the current front velocity decreases more rapidly as $t^{-4/5}$, with front position advancing as $t^{1/5}$ [14].

However, [2, 3, 4, 8, 9, 13, 15] have also considered density currents theoretically, experimentally and numerically investigating the evolution of the frontal head in both rough and smooth surfaces. Both three and two regimes of flow were also recorded in the the entire process which also depends on the lock-volume. First was the slumping or a rapid collapsing phase, during which the current is retarded by the counterflow in the fluid into which it is issuing. Though, motion in the surrounding fluid plays a negligible role in this phase. [9] reported that outside the effects of back reflected waves on the current and initial volume, the front spreading distances and front velocities of the currents developed very smoothly. But then, effect of drag and friction were significant. Though, their results show some sort of variations as time progresses, which differs from those by previous authors on gravity current flows of small-volume release. Theoretical results show that the front traveling length over time is a quadratic function and the front velocity decreases linearly based on the initial speed, which is related to the drag coefficient. All these were analysed using a one-layer hydraulic theory. It was reported that bottom roughness elements does affect the gravity current propagation. For small elements, the current flow was more like those with a smooth bottom, while for larger elements, the propagation speed reduces together with the internal structures of the current: both the head and the tail in this case was also significantly modified [4, 13]. These authors [3] have also investigated Density Current flows and was able to identify three regimes. The general behaviour in that study was dependent on lock volume, density difference and Reynolds number as also described by [8]. They recorded a collapsing velocity of the denser fluid within the first time frame and described it to be higher than every fluid movement elsewhere, and as well relations that describes the various regimes of flow. Though, there are variations in the scaling laws as compared to the earlier studied cases [8, 12, 15]. It is believed that the velocity of the gravity current is highly influenced by density difference and lock volume (i.e., velocity increases with increasing density difference for those where density variation is as a result of saltwater and a considerably high lock volume).

Their ([15]) results show that cross section of the tank played a vital role in the propagation of gravity currents. Especially, the presence of the trapezoidal shape at the bottom of the composite cross section results in a significant increase in the velocity of the gravity currents in comparison with the rectangular cross section. The current with the greater density difference travels faster than the others in all cases (i.e., velocity of the gravity current increases with increasing density difference) even as the gravity current propagates with a parabolic head. Though, effect of density difference is more pronounced in the case of composite section than in the case of trapezoidal section. These authors [2] have also carried out an investigation on the behaviour of warm discharge through lock exchange, with the assumption that density was taken as a quadratic function of temperature. It was reported that their results appear very similar to the experimentally studied cases by Marmoush et al. [16] and Bukreev [17], with some level of Rayleigh-Taylor instabilities as warm water penetrate the ambient fluid as surface current. Though, they were unable to observe the slumping phase and the viscous phase as described in most of the earlier investigations [8, 11]. This is due to the fact that cabbeling process begins immediately we assume gate removal. And as denser fluid at T_m is produced at every point in the surface current that sink to the floor due to cabbeling. This process causes a sudden decrease in velocity of the frontal head right from the start of the simulation, and this in turn resulting to a quick halt of the surface current.

In most of the configurations, the lock-exchange method is used (see Fig. 1): as this enables such flow scenarios over the rough and smooth horizontal surfaces and as well as the inclined surfaces [2, 3]. In most of the experimental studied cases, salt is frequently used to create the density difference in fresh water except for [2, 3, 17] where density difference is as a result of temperature. In this case, cabbeling process is key even as the various fluids advances in their opposite directions. This behaviour can usually be seen in lakes, especially in holomictic lakes and warm discharge from thermoelectric power generating plants (see [2, 18, 19]) for more insights and a more detailed literature review. However, we have recently carried out a Numerical investigation entitled "Density Current Simulations In Cold Fresh Water And Its Cabbeling phenomenon: A Comparative Analysis With Given Experimental Results" where we have extensively discussed the behaviour of such flows, taken density as a quadratic function of temperature. Three regimes of flow were also identified together with the development of Kelvin-Helmholtz instability as recorded in earlier investigations. Relations were drawn that describes the propagation speed of the frontal head and as well as the distance traveled with respect to time [3]. Though, these Relations were drawn from simulations with computational domain length $L = 10000$, i.e., $0 \leq X \leq 10000$, with a domain height $H = 1200$ i.e., $0 \leq Y \leq 1200$ with barrier position $0.07L/14$. We also recorded that the collapsing velocity of the denser fluid within the first time frame was high, higher than every fluid movement elsewhere. We have also claimed that the velocity of the gravity current is highly influenced by density difference and lock volume [3]. Thus, the consideration of barrier position is key, being that the lock volume is also believed to be a factor. Then, there is the need to carryout another investigation repositioning the barrier position to fathom, if the speed of the current is really and also dependent on the barrier position. Thus, we can see this as a limitation in the previous investigation. This is very important because numerical simulations are mainly conducted in a finite domain and as such, most of the lock volumes are also small, as this in turn perturb the free flow of the current by the back reflected waves which is also a limitation in previous studies. Thus, it will also be interesting if measures can be taken to minimise or eliminate the effect of this back reflected waves in other to properly fathom the behaviour in the propagation of the frontal speed after the slumping phase.

For this reason, we will carryout a detailed investigation so as to better fathom and as well, gain more insight into such studies. Thus, taken into consideration here is the motion of fluids with T_m (which is $3.98°C$ for fresh water at atmospheric pressure, (i.e., approximately $4°C$ in some numerical calculation)) initially at rest but separated by a vertical barrier at the center in a rectangular domain with an ambient fluid with temperature zero. As usual, It is expected that difference in the hydrostatic pressure will result in the denser fluid flowing in one direction along the floor once the barrier is lifted up. Meanwhile the less dense fluid will flow in the opposite direction horizontally along the upper part of the domain, and this in turn create a mixing layer between the two fluids as they interact with each other. [2, 3] However, the interaction process will continue even as the most dense fluid is located at the lower part with a frontal or leading head penetrating the ambient fluid. This will continue until the dense but warm fluid will mix to a point where both fluids attain the same temperature. [2, 3]

Our present investigation is based on numerical simulations that uses the lock exchange method with the assumption that density is a quadratic function of temperature. Density current which contains a dense

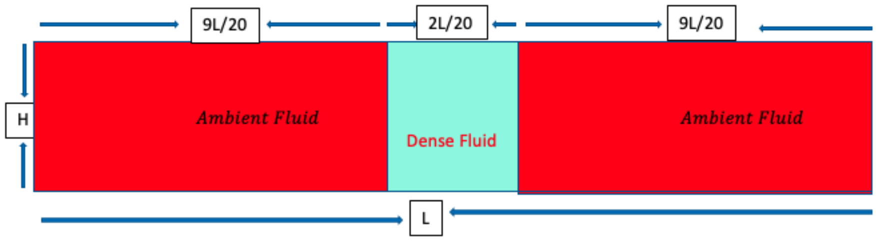


Fig. 1: Schematic presentation of Lock-exchange flow in a channel of length L and height H.

but warm fluid in this case is expected to mix further as it spreads outward on the floor. This will continue until the dense fluid will mix to a point where it attain the same temperature with the ambient fluid [3].

Computational domain length and height will be kept constant, where length $L = 20000$, i.e., $0 \leq X \leq 20000$, and a domain height $H = 1500$ i.e., $0 \leq Y \leq 1500$, barrier position is at $9000 \leq 2L/20 \leq 11000$. The input fluid (lock volume) temperature is $\phi_{in} = 1$ at the centre of the domain. Meanwhile, on the left and right hand side (ambient fluid) is $\phi_{in} = 0$. Where L is the total length of the computational domain and ϕ_{in}, the initial temperature on the various sides of the barrier and the centre.

2 Model Formulation and Governing Equations

The behaviour of the frontal head in density currents as denser fluid spread outwards on the floor after the lock release due to the nonlinear relation between density ρ and temperature T is very important. Thus, the relation below is useful for this study,

$$\rho = \rho_m - \beta(T - T_m)^2 \tag{1}$$

This, we believe gives a very good fit to the experimentally determined density of fresh water at temperature below $10°C$ if we consider $T_m = 3.98°C$, $\rho_m = 1.000 \times 10^3\ kg.m^{-3}$ and $\beta = 8.0 \times 10^{-3}\ kg.m^{-3}(°C)^{-2}$ [20, 21] and all other fluid properties (e.g. viscosity, thermal diffusivity) are assumed constant. We also assume that the flow is time dependent and two dimensional, and that the liquid property is constant except for the water density, which changes with temperature and in turn results to the buoyancy force. We can non-dimensionalise the coordinates x, y, velocity components u, v, time t, pressure p and temperature T by

$$U = \frac{u}{U_*} \quad V = \frac{v}{U_*} \quad X = \frac{x}{H} \quad Y = \frac{y}{H} \quad \tau = \frac{t}{\frac{H}{U_*}} \quad P = \frac{p}{\rho U_*^2}$$

$$\phi = \frac{T - T_\infty}{T_m - T_\infty}, \tag{2}$$

where x and u are horizontal, y and v are vertical; $U_* = \sqrt{\frac{\rho_\infty - \rho)}{\rho} H}$ is the relative frontal velocity and domain height H. We also define dimensionless parameters, the Reynolds Re, Prandtl Pr and Froude Fr numbers, by

$$\nu = \frac{\mu}{\rho} \quad \alpha = \frac{k}{\rho c_p} \quad Re = \frac{U_* H}{\nu} \quad Pr = \frac{\nu}{\alpha} \quad Fr^2 = \frac{\rho_m U_*^2}{g\beta(T_m - T_\infty)^2 H}, \tag{3}$$

where ν and α are the respective diffusivities of momentum and heat, and μ is viscosity, k is thermal conductivity and c_p is specific heat capacity. In terms of these dimensionless variables and parameters, the continuity equation, the horizontal and vertical momentum equations and the thermal energy equation are given as

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{4}$$

$$\frac{\partial U}{\partial \tau} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{Re}(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}) \tag{5}$$

$$\frac{\partial V}{\partial \tau} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{Re}(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}) + \frac{1}{Fr^2}[\phi^2 - 2\phi] \tag{6}$$

$$\frac{\partial \phi}{\partial \tau} + U\frac{\partial \phi}{\partial X} + V\frac{\partial \phi}{\partial Y} = \frac{1}{RePr}(\frac{\partial^2 \phi}{\partial X^2} + \frac{\partial^2 \phi}{\partial Y^2}) \tag{7}$$

The terms U_{dc} are used to describe the propagating speed of the density current.
Our initial conditions are an undisturbed, homogeneous medium as also given in [3].

$$U = 0, \quad V = 0, \quad \phi = 0, \quad for \quad \tau < 0 \tag{8}$$

For $\tau \geq 0$ we have boundary conditions as follows. On the side walls:

$$U = 0, \quad V = 0, \quad \frac{\partial \phi}{\partial X} = 0 \tag{9}$$

At the plume source:

$$U = U_*, \quad V = 0, \quad \phi_{in} = 1 \text{ for } 2L/20 \text{ and } \phi_{in} = 0 \text{ for } 9L/20 \text{ and } 9L/20, \quad \text{for} \quad X = 0, \, at \; Y = H \tag{10}$$

On the floor of the domain:

$$U = 0, \quad V = 0, \quad \frac{\partial \phi}{\partial Y} = 0 \tag{11}$$

At the top of the domain:

$$\frac{\partial U}{\partial Y} = 0, \quad V = 0, \quad \frac{\partial \phi}{\partial Y} = 0 \tag{12}$$

The Froude number $Fr = 1$ and Prandtl number $Pr = 11$ will be fixed throughout this investigation varying Reynolds number between $Re = 50$ *and* 100. The dimensionless temperature $\phi_{in} = 1$ at the centre is equivalent to a discharge at $4°C$ into an ambient at $0°C$. Numerical solution of the above equations is by means of COMSOL Multiphysics software. This commercial package uses a finite element solver with discretization by the Galerkin method and stabilisation to prevent spurious oscillations. We have used the "Extremely fine" setting for the mesh. Time stepping is by COMSOL's Backward Differentiation Formulas. Further information about the numerical methods is available from the COMSOL Multiphysics website [22]. Results will be illustrated mainly by surface temperature plots of dimensionless temperature on a colour scale from dark red for the ambient temperature $\phi = 0.0$, through yellow to white for the source temperature $\phi = 1$. Note that $\phi = 1.0$ corresponds to the temperature of maximum density.

3 Results

The behaviour of warm fluid, discharged at $4°C$ through lock-exchange in cold fresh water was investigated and shown in Figure 2, & 3 . Froude number $Fr = 1$ and Prandtl number $Pr = 11$, are kept fixed throughout the study, varying Reynolds number between $Re = 50$ *and* 100. Computational domain length and height was kept fixed with lock-volume at the centre of the domain. Where length $L = 20000$, i.e., $0 \leq X \leq 20000$, and a domain height $H = 1500$ i.e., $0 \leq Y \leq 1500$. The evolution of temperature field for $\phi_{in} = 1$ within the time frame $0 \leq \tau \leq 470$ for Reynolds number $Re = 100$. is only shown in this case because both results appear similar.
After the lock release, a speedy movement of the lock volume at the centre of the container was observed

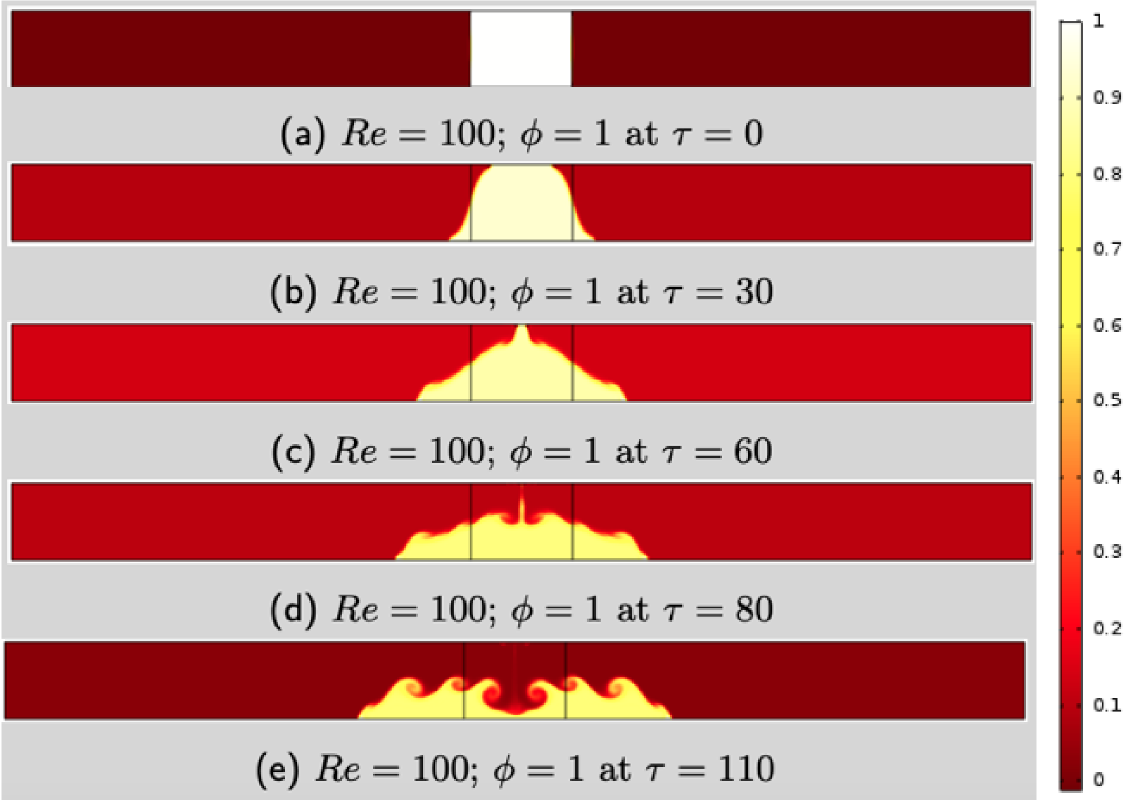


Fig. 2: Evolution of temperature field in the Density current for $Fr = 1$ and Reynolds number $Re = 100$ with $\phi = 1$ at time $0 \leq \tau \leq 110$

with a leading head at two front on the floor, one heading towards the left hand side and the other to the right hand side. The overall shape of the lock volume at this point is more like the hat (see Fig. 2b). Cabbeling process also commenced immediately after the lock release, at the point where the water masses meet; though, this is not too apparent as significant mixed fluid was not noticed in the density current. It is believed that fluid movement in the collapsing phase is not totally independent of lock volume but independent of the back reflected waves that seem to affect the free flow of the current in previous studies [2, 3, 6, 9]. It is also believed that the phase wherein these behaviours are described, is the first regime as also evident in (Fig. 4(a), 5(a)). It is also worth noting that the speedy movement of fluid in this collapsing phase might not only be to the influence of the small lock volume [23] but also to the fact that denser fluid could flow from two fronts. Unlike those where denser fluid is positioned at one end of the container [2, 3, 23].
As time progresses, the entire lock volume collapsed uniformly before splitting into two equal halves and began to form density current (see Fig. 2c - 2e). There is no effect of back reflected waves on the current instead, the development of Kelvin-Helmholtz instabilities at the interaction layer between the ambient and the denser fluid was observed.
Afterwards, a fully developed stage of these Kelvin-Helmholtz instabilities at the interaction layer between the ambient and the denser fluid was observed (see Fig. 3(f - j)) even as the penetrating sharp head of the current advances forward, leaving fluid that have attained $\phi_{in} = 0$ at the rear. But then, simulations with increased lock volume show that a ground flow of warm but dense fluid from the rear continue to

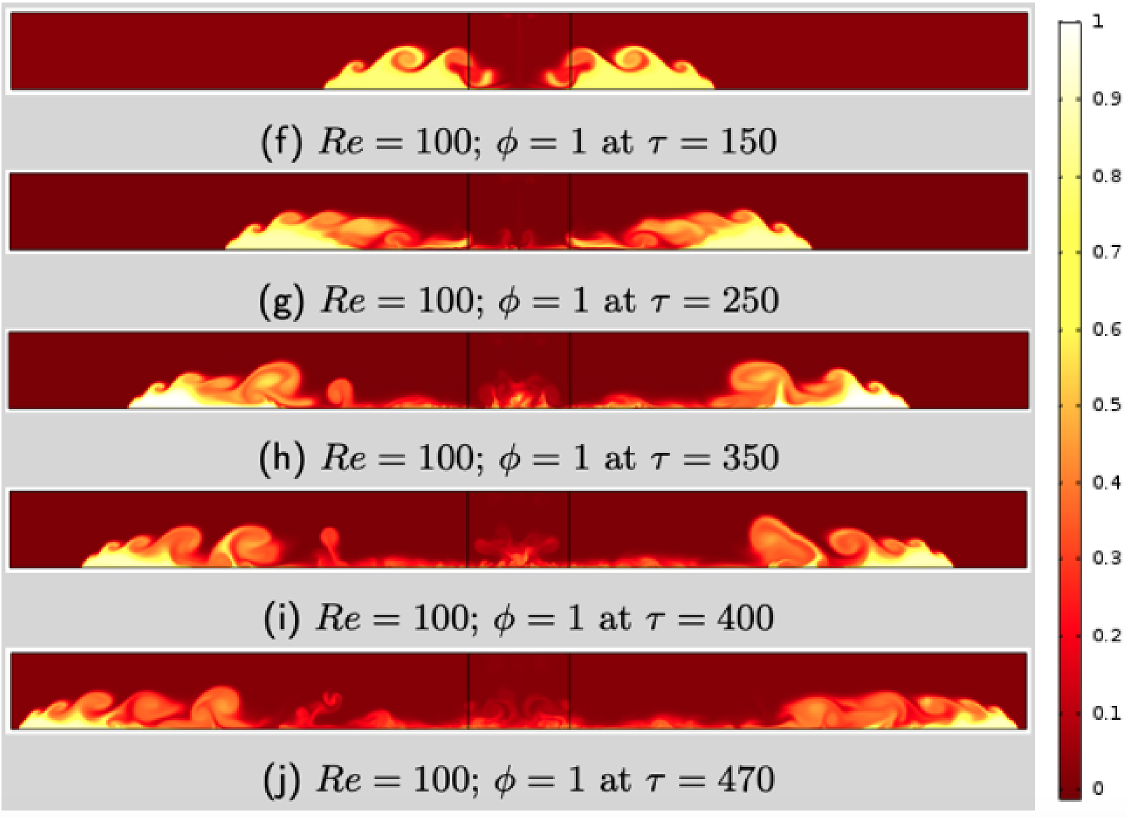


Fig. 3: Evolution of temperature field in the Density current for $Fr = 1$ and Reynolds number $Re = 100$ with $\phi = 1$ at time $150 \leq \tau \leq 470$

Table 1: Relations describing the propagation speed of the density current U_{dc} as a function of time τ_n for simulations with $Re = 50$

Regime of Flow	U_{dc} Formula	Regression Coefficient R^2
1st	$\approx 0.8776\tau_n^{0.9716}$	≈ 0.9972
2nd	$\approx 35.108\tau_n^{-0.077}$	≈ 0.5252
3rd	0	0

Table 2: Relations describing the propagation speed of the density current U_{dc} as a function of time τ_n for simulations with $Re = 100$

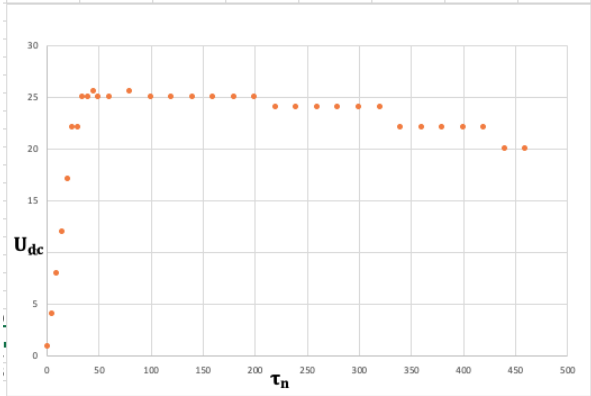
Regime of Flow	U_{dc} Formula	Regression Coefficient R^2
1st	$\approx 0.9064\tau_n^{0.9812}$	≈ 0.9942
2nd	$\approx 29.375\tau_n^{-0.034}$	≈ 0.3358
3rd	0	0

replenish this head, enabling the frontal head to penetrate the ambient fluid faster. Though, density difference between ambient fluid and dense fluid is very small, thus mixture requires just a little mixing before attaining $\phi_{in} = 0$. This implies that the density current will eventually halt if this is conducted in an infinite length [3]. This we also believed to be the second regime or phase of flow as evident in (Fig. 4(a), 5(a)) with a linear scale. In this investigation, we could only identify two regimes of flow with a stepwise decreasing velocity in the second phase. The possible explanation to this stepwise behaviour might be as a result of the regrouping process after the raging columns of the Kelvin-Helmholtz instabilities that have partitioned the denser fluid. This process is expected to continue until the denser fluid will attain the same temperature with the ambient fluid and the density current will eventually halt [3].

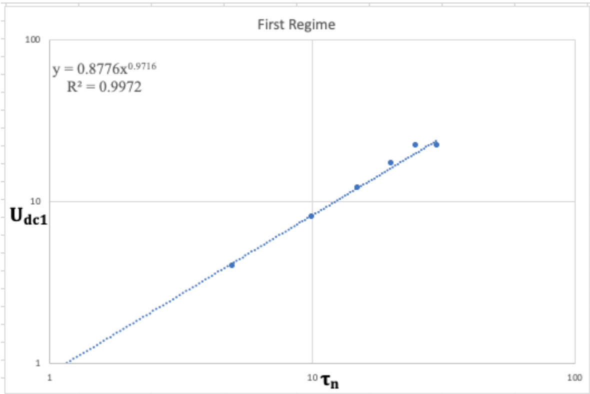
Results here show that the velocity with which the current travels with in the second regime of flow, is higher within the first time frame than those by [3, 9, 23] with the effect of back reflected waves (see Fig. 4(a), 5(a) with a linear scale). Meanwhile, speed of the current in the first regime of flow appear more like those by [3, 23] with small lock volume. This is also evident in Table 1 and 2, where we have obtained some empirically determined data set that represent the best fit power laws obtained by linear regression of $logU_{dc1}$ on $log\tau_n$. In like manner, we have also obtained some empirically determined data set that represent the best fit power laws obtained by linear regression of $logU_{dc}$ on $log\tau_n$ in the second regime of flow. This is also evident in Table 1 and 2. It has been established that gravity currents usually undergo either two or three distinct phases of flow and these include: a slumping phase, self-similar phase and viscous phase [9, 11, 23] but that this is also dependent on the lock volume. This authors [23] have established that number of distinct phases of flow are dependent on the lock volume (i.e., two phases of flow when the lock volume is big and three phases of flow when the lock volume is small). Thus, having identified two regimes here, we can the say that the lock volume used is fairly big. One major factor that is responsible for decrease in the velocity here is mixing.

Because mixture here requires a very little mixing before it attain the same density with the ambient fluid $\phi_{in} = 0$, the strong interaction between the two fluids also contributed to the slow movement of the current at much later time. Even though the choice of numerical parameters (Reynolds number 50 and 100) for a laminar flow was suggested and ideal for the purpose of this work [2, 3, 23]. It is worth emphasising that in most of the lock-exchange experimental cases, salt is mostly used to create the density difference. Except for Bukreev [17, 24] who considered density variation as a result of temperature difference, but did not really give much details. Though, [2, 3, 23] have extensively discussed gravity current flows but did not consider the effects of back reflected waves which is the main focus of this paper to either minimise or eliminate these effects.

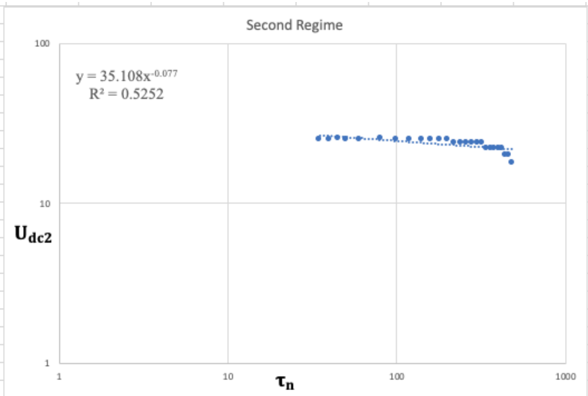
Previous results have also shown that the front velocities in the collapsing phase are independent of lock volume [9]. But this seem not to be the same here because we have highlighted above that a speedy movement of the lock volume at the centre of the container was observed with a leading head at two front on the floor, one heading towards the left hand side and the other to the right hand side. Thus, the lock



(a) Linear Scale

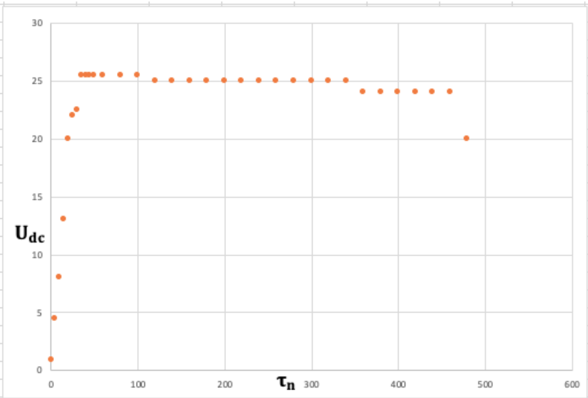


(b) Logarithmic Scale

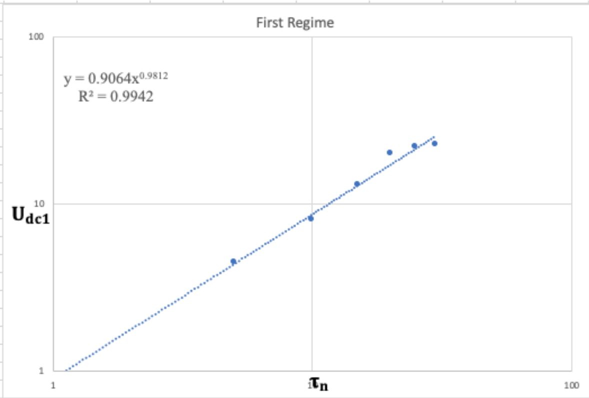


(c) Logarithmic Scale

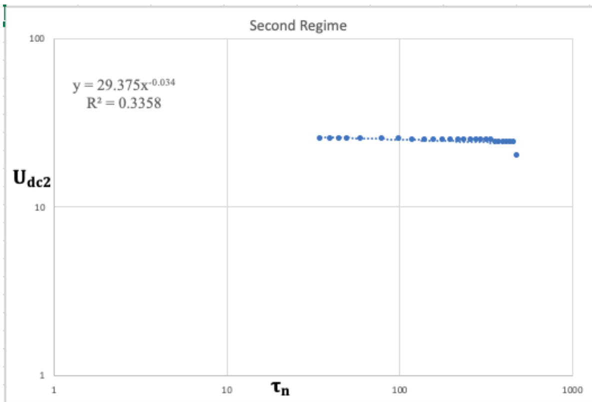
Fig. 4: Propagation speed of the Density current U_{dc} for the different Regimes with respect to time τ_n for simulations with $Re = 50$.



(a) Linear Scale



(b) Logarithmic Scale



(c) Logarithmic Scale

Fig. 5: Propagation speed of the Density current U_{dc} for the different Regimes with respect to time τ_n for simulations with $Re = 100$.

volume position may also influence the speed of the current. Thus, the fluid movement in the first phase (regime) is not totally independent of the lock volume [23] and its position here, where density difference is as a result of temperature. Lastly, it may also be possible that power law does not fit well in all the flow processes as we have indicated previously [8, 23], though, this was not showed clearly. However, our scaling power laws here is the second phase show some variations with previous studies by [3, 23] where we have effect of back reflected waves. But results in the collapsing phase here are in strong agreement with those in the first phase of our previous simulations with small lock volume [23]. Furthermore, these numerical simulations are mainly conducted in a finite domain and as such, we may not be privileged to observe the halting process of the current especially when a reasonable amount of lock volumes is used. Thus, this we can see as a limitation here in this investigation. However, the general behaviours here are dependent on lock volume, barrier position, density difference and Reynolds number. We strongly believe that this work as presented here is practical and can also enhance policy making towards the protection of the aquatic ecosystems.These information as presented will enable researchers to better fathom and as well, gain more insight into such flows.

4 Summary/Conclusion

The behaviour of warm water discharged at $4°C$ through lock-exchange in cold fresh water was investigated numerically. Simulations were conducted using $Fr = 1$, $Pr = 11$, and varying Re between 50 and 100, fixing lock-volume at the centre of the domain. The results here show a speedy movement of the lock volume at the centre of the container with a leading head at two front on the floor which resulted in a hat shape within the first few time frame. Fluid movement in the second phase is independent of the back reflected waves. As time progresses, the entire lock volume collapsed uniformly before splitting into two equal halves and began to form density current (see Fig. 2c - 2e). A fully developed stage of the Kelvin-Helmholtz instabilities at the interaction layer between the ambient and the denser fluid was observed (see Fig. 3(f - j)). We were able to identify two regimes of flow with a stepwise decreasing velocity in the second phase. Our results have shown that velocity with which the current travels with in the second regime is higher within the first time frame than those by [3, 9, 23] with the effect of back reflected waves (see Fig. 4(a), 5(a). One major factor that is responsible for decrease in the velocity here is mixing. Because mixture here requires a very little mixing before it attain the same density with the ambient fluid.
Previous results have also shown that the front velocities in the collapsing phase are independent of lock volume [9]. But this seem not to be the same here because fluid movement in the first phase (regime) is not totally independent of the lock volume [23] and its position here, where density difference is as a result of temperature. However, our scaling power laws here is the second phase show some variations with previous studies by [3, 23] where we have effect of back reflected waves. But results in the collapsing phase here are in strong agreement with those in the first phase of our previous simulations with small lock volume [23]. It may also be possible that power law does not fit well in all the flow processes as we have indicated previously [8, 23], though, this was not showed clearly. Furthermore, gravity current simulations are mainly conducted in a finite domain and as such, we may not be privileged to observe the halting process of the current especially when a reasonable amount of lock volumes is used. Thus, this we can also see as a limitation as we were unable to capture the end behaviour. Generally, the spreading behaviour here is dependent on lock volume, barrier position, density difference and Reynolds number. This work as presented here is practical and relevant to many fields of study and also enhances policy making towards the protection of the aquatic ecosystems. Because such discharge or introduction of warm but dense water may definitely give rise to environmental problems; where the sudden increase in the water temperature after discharge/introduction will lead to "thermal shock" killing aquatic life that has become acclimatised to living in a stable temperate environment. Researchers can also gain more knowledge in terms of the dynamics of such flows.

References

[1] Ungarish, M. (2021) *Gravity Currents and Intrusions: Analysis and Prediction.* USA, World Scientific Publishing Co. Pte. Ltd.

[2] George, M. A. and Kay, A. (2022). Numerical Simulations of the Cabbeling Phenomenon in Surface Gravity Currents in Cold Fresh Water *Journal of Scientific Research & Reports* **28***(1)* Pp. 68 - 85.

[3] George, M. A. and Osaisai, F. E. (2022). Density Current Simulations In Cold Fresh Water And Its Cabbeling phenomenon: A Comparative Analysis With Given Experimental Results *Current Journal of Applied Science and Technology* **41***(29)* Pp. 37 - 52.

[4] Nasrollahpour, R., Jamal, H. M., Ismail, Z., Ibrahim, Z., Jumain, M., Haniffah, R. M. M and Ishak, S. M. D. (2021). *Velocity Structure of Density Currents Propagating Over Rough Beds. Water,* **13** 1460.

[5] Simpson, J. E. (1997) *Gravity Currents: In the Environment and the Laboratory.* UK, Cambridge University Press, 258 pp.

[6] Nogueira, H. I., Adduce, C., Alves, E. and France, J. M. (2014). *Dynamics of the head of gravity currents. Journals of Environmental Fluid Mechanics,* **14** Pp. 519 - 540.

[7] Tien, N. N., Uu, D. V., Cuong, D. H., Mau, L. D., Tung, N. X. and Hung, P. D. (2020). *Mechanism of Formation and Estuarine Turbidity Maxima in the Hau River Mouth. Water,* **12** 2547.

[8] Huppert, H. E. and Simpson, J. E (1980). *The Slumping of Gravity Currents. Journal of Fluid Mechanics* **99** Pp. 785 - 799.

[9] Yin, X., He, Y., Lu, C., Gao, S. and Liu, Q. (2020). *Experimental Study on Front Spreading of Lock-Exchange Gravity Current with Long Lock Length. Journal of Engineering Mechanics,* **146***(1)* 04019113 (1-11).

[10] Dai, A. and Huang, Y. L. (2020). *Experiments on gravity currents propagating on unbounded uniform slopes. Environ. Fluid Mech.,* **20***(6)* Pp. 1637 - 1662.

[11] Rottman, J. W., and Simpson, J. E. (1983). *Gravity currents produced by instantaneous releases of a heavy fluid in a rectangular channel. Journal of Fluid Mechanics,* **135,** Pp. 95 - 110.

[12] Nogueira, I. S. H., Adduce, C., Alves, E. and France, J. M. (2013). *Analysis of Lock-exchange gravity currents over smooth and rough beds. Journal of Hydraulic Research,* **51***(4)* Pp. 417 - 531.

[13] Maggi, R. M., Adduce, C. and Negretti, E. M. (2022). *Lock release gravity currents propagating over roughness elements. Environmental Fluid Mechanics,* Pp. 1 - 20.

[14] Simpson, J. E. (1982). *Gravity currents in the laboratory, atmosphere, and ocean. JAnnu Rev Fluid Mech,* **14***(1)* Pp. 213 - 234.

[15] Vardakostas, S., Kementsetsidis, S. and Keramaris, E. (2020). *Saline Gravity Currents with Large Density Difference with Fresh Water in a Valley of Trapezoidal Shape. Environ. Sci. Proc.,* **2***(64)* Pp. 1 - 9.

[16] Marmoush, Y. R., Smith, A. A. and Hamblin, P. F. (1984). *Pilot experiments on thermal bar in lock exchange flow. Journal of Energy Engineering,* **110***(3)* Pp. 215 - 227.

[17] Bukreev, I. V. (2006). *Effect of the Nonmonotonic Temperature Dependence of Water Density on the Propagation of a Vertical Plante Jet. Journal of Applied Mechanics and Technical Physics,* **47***(2)* Pp. 169 - 174.

[18] George, M. A. and Kay, A. (2017). Numerical simulation of a line plume impinging on a ceiling in cold fresh water *International Journal of Heat and Mass Transfer* **108** Pp. 1364 - 1373.

[19] George, M. A. and Kay, A. (2016). Warm discharges in cold fresh water: 2. Numerical simulation of laminar line plumes *Environ. Fluid Mech.* doi: http://dx.doi.org/10.1007/s10652-016-9468-x.

[20] Moore, D. R. and Weiss, N. O. (1973). Nonlinear penetrative convection. *Journal of Fluid Mechanics,* **61** Pp. 553 - 581.

[21] Oosthuizen, P. H. and Paul, J. T. (1996). A Numerical study of the Steady State Freezing of Water in an open Rectangular Cavity. *International Journal of Numerical Methods for Heat and Fluid Flow,* **6***(5)*, Pp. 3-16

[22] COMSOL Multiphysics Cyclopedia. *The Finite Element Method (FEM). [ONLINE] Available at: https://www.comsol.com/multiphysics/finite-element-method [Accessed 28 April 2016].*

[23] George, M. A. and Osaisai, F. E. (2022). A Numerical Study of the behaviour on Lock Volume Variations in Lock-Exchange Density Current In Cold Fresh Water. *Journal of Scientific Research & Reports* **28***(10)* Pp. 125 - 141.

[24] Bukreev, I. V. (2006). *Effect of the Nonmonotonic Temperature Dependence of Water Density on the Decay of an initial Discontinuity. Journal of Applied Mechanics and Technical Physics,* **47***(1)* Pp. 54 - 60.