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Study of the Effect of a Cooling Load on a Fluid Surface (Water) in an Open Channel

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ABSTRACT

In this study the effect of cooling load on the surface water of an open channel with different flow depths is investigated. The method, which was used, involves an experimental laboratory set-up that contains a well-insulated cooling load over a finite area of the water surface, without direct contact with the free water surface so that losses of load to the environment should be avoided. The different cooling loads for each experiment were achieved with the use of insulating films. The insulating film is placed at the bottom of the experimental set-up where there was an empty surface (gap - D), through which the cooling load is allowed to pass. The measurement of velocities was carried out at a two-dimensional (XZ) field, with the help of a digital camera. The recording of motion of the dye (rhodamine) along the channel per unit of time, allows the calculation of the values of the velocity fields. Measurements were conducted when the phenomenon becomes steady. The results for the determination of the cold mass length as a function of the flow depth, and the temperature difference ΔT, in a state of thermal equilibrium, led to the formation of a new mathematical relationship. Further study of the phenomenon is essential for the improvement of this study, in combination with other parameters that affect the aquatic ecosystem.

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Conductivity
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Cool transfer
Mass transfer

1. INTRODUCTION

The effect of the cooling load on the water surface of an aquatic system has been studied experimentally in a laboratory simulating real conditions, such as those in a lake or a river.

In the present study the effect of cooling on the surface water mass of an open channel which is applied over an area of 50 cm X 50 cm is described. According to the results of the experiments, the generation of velocity fields was found due to the temperature difference between two regions with an average temperature of T1 in the one and T2 in another area (Fig.1).

A characteristic motion of the water mass between these two areas can be observed. This motion from one area to another is due to the different water densities that result under the influence of the applied cooling load. Initially this motion is constantly changing and eventually becomes steady under the condition of a constant cooling load in the T1 region.

The research questions that this study aims to answer are as follows:

1. Watershed issues for the water supply use of an area. This knowledge is valuable in the installation of the water intake so that high-temperature water does not drain.
2. The determination of the maximum length of cold mass that will be developed in cold liquid, for masses that are discharged at a recipient.
3. Information on the vertical change of the water temperature in the water column of a basin which is heated by solar radiation.
4. The process of liquid waste pollutant dispersion in water receivers, e.g., lakes, seas, etc.
5. The response of surface water masses to temperature changes in the water, since it is a determining factor for the study of a freshwater ecosystem. This research is crucial in a climate change environment.

The objectives of this research are:

- The simulation of the natural phenomenon of the cooling effect on the water surface of an open channel in a laboratory environment.

NOMENCLATURE

u	mean velocity fields on the channel axis (X)	h	flow depth
ΔT	T_o- T_v (final temperature – initial temperature)	L	channel length
ρ	density	X	axial flow coordinate
T	temperature	Y	transverse component of the system systemic
t	time	Z	vertical component of coordinates
a	coefficient		

- The effect of the cooling load on the water surface, that was studied experimentally in laboratory conditions, for the simulation with natural conditions, such as a lake or a river.
- The determination of the way in which the local water cooling is transferred to the rest of the initially still water masses of the channel.
- The calculation of temperature distribution in the field in each location along the channel (Isothermal curves).
- The calculation of the field of velocities in two dimensions (2D flow with the water flow along channel in axis X and waters' depths in axis Z), which is generated through the temperature difference and consequently through the difference in fluid density at different locations.
- The calculation of the final length of the cooling masses motion, when the phenomenon becomes steady and thermal equilibrium is reached.

The most essential problem in this research is the attempt to achieve uniform cooling transfer across the channel cross-section, on which the cooling load was applied. This was solved by applying strips to the bed of the device with different D gaps. In this way, the cooling load was maintained for as long as needed to curry out the experiments.

According to the literature, there are few studies which focus on the same or similar research. However, there are some interesting studies on similar issues as summarized below.

Ashton (1986) studied the motion of ice in rivers and lakes with the aim of protecting human life and the environment from the harmful effects of ice. A major part of the study can be applied to issues associated with saline ice.

Joss & Resele (1987) developed a mathematical model that involves heat exchange between a river and the atmosphere. The boundary conditions change with short time steps, so that representative values of the influencing parameters are used.

Wang & Martin (1991) used analytical methods for natural heat as a tracer and for the quantification of surface-groundwater exchange. Some of the study's conclusions are that hydraulic conductivity can be changed significantly over time, but detailed uncertainty analysis is required (e.g., Monte Carlo), and the reliability of the method must be ascertained. The evaluation was done using field temperature recording.

Dow-Ambtman (2009) studied ice processing models based on empirical relationships. Experimental studies were conducted in a laboratory in order to add knowledge that concerns the physical behavior of ice cubes in water and the hydrodynamic forces acting on them.

Dow-Ambtman (2009) conducted experiments on a recirculated pipeline. The aim was the natural behavior of the ice islets in the water and the hydrodynamic forces acting on them. The pressure distribution of the rotation effect on the ice islet was also investigated. The velocity field was measured using a digital particle image.

Laura & Claude (2010) studied the interactions between ice and climate of a lake. The results showed that stresses in ice have usually been associated with fluctuations in air temperatures, while stresses in ice thickness tend to be more associated with changes in snow cover. The possibility of modeling the ice climate of the lakes was also examined.

Jha & Ajibade (2010) investigated the flow and mass transfer in a channel formed by two vertical parallel plates. The phenomenon of thermal diffusion was also investigated. Velocity, temperature, and concentration profiles were calculated using the Laplace transformation technique and were used to calculate the shear stress, Nusselt number, and mass flow. It was observed that the phenomenon of thermal diffusion creates an abnormal condition in the temperature and velocity profiles for small Prandtl numbers.

Rau et al. (2010) applied two methods for natural heat as a tracer and for the quantification of surface-groundwater exchange, which were verified by field data. The flow was multidimensional and dynamic. Relevant limitations were used on the applied methods.

Kalinowska et al. (2012) developed a two-dimensional model, for the heating and cooling in flowing water. More specifically, two models were developed; one for the evaluation of the two-dimensional turbulent velocity field and the other for two-dimensional heat transfer in open channels. Similar scenarios were presented for the spread of the heated water in a gas-fired power station on the Vistula River. Out of four (4) different scenarios, the most environmentally friendly discharge of thermal pollution was chosen.

Jasikova et al. (2013) studied experimentally the fluid flow within a model of a stratification tank with a heat exchanger. The results provided valuable information about the behavior of the fluid inside the tank model, which is helpful for the verification and validation of models and simulations.

Through a model, Kalinowska & Rowiński (2014) studied the changes in the water temperature of a stream in which a significant amount of thermal pollution was introduced. An overview of mathematical solving techniques suitable for quantifying heat transfer was created. The models that presented ranged from 3D (aimed at short distances) to the 1D approach (which allows modeling heat transfer over long distances). Particular attention was placed on 2D (two-dimensional) models, which is especially useful for the examination of thermal pollution, such as the heat which is discharged from a steam power station.

Blythman (2017) studied the parametric analyses of hydrodynamics and heat transfer in a rectangular channel, using experimental measurements, analytical solutions, and numerical CFD simulations. The results showed that the temperature profile is mainly formed by fluid displacement versus the axial temperature gradient, although he observed significant thermal diffusion for low Prandtl number.

Kalinowska (2019) studied the practical problems associated with the spread of thermal pollution in rivers. An attempt was made to predict the increase of water temperature, and the processes that change the water temperature were studied. Emphasis was placed on water-to-air heat exchange.

Kulkarni & Hinge (2017) studied a new compound broad crested weir structure for discharge measurement. The experiments include an obstruction in an open channel, resulting in an equation for various discharge capacities. Finally, an improved estimation of discharge coefficient with less variation for the weir was proposed.

Ajibade & Ojeagbase (2020) studied viscosity and thermal conductivity change in a two-dimensional fluid flow with constant density. Numerical solutions for velocity, temperature, and magnetic field profiles were determined using the differential transformation (DTM) method. The results showed that as the viscosity parameter increases and the thermal conductivity parameters decrease, the velocity of the fluid decreases in the boundary layer.

Kulkarni & Hinge (2020) developed a new weir structure for measurement of discharge weir model which is modified for achieving optimal results, thereby resulting in the reformed discharge coefficient values.

Kalinowska and Rowinski (2015) studied the modeling of the temperature of a watercourse, specifically after introducing some thermal pollution. Particular attention was paid to two-dimensional, depth average, models, examining the route of thermal pollution such as the heat discharged from a steam power station.

Shublaq & Sleiti (2020) investigated water evaporation losses in cooling towers. This research recommends the use of filters to limit the losses at the top of the tower, and especially aluminum metal panel filters, which seem to have the best results.

Amjad et al. (2021) studied heat transfer in a nanofluid flow under a magnetic field and thermal radiation in a narrow channel. Laminar flow simulations were performed in a two-dimensional (2D) domain. The effects of variations in Hartmann number, Strouhal number, Prandtl number, and thermal radiation parameter are analyzed to compare the flow characteristics and heat transfer rate. The equations governing these conditions are solved numerically using the finite element method.

Kulkarni & Hinge (2021) used analytical methods to develop a model with compound weirs discharge. The results were analyzed and the CFD model was validated. Also, the weir performance with accurate estimates between theoretical, experimental and CFD outputs was validated.

Kulkarni & Hinge (2022), conducted a comparative study of experimental and CFD analysis for predicting discharge coefficient of compound broad crested weir. The hydraulic research for measuring discharge numerically is carried out using the well-known software FLOW 3D. The results showed that the relative average error was around 5%.

Tarrad (2022) developed a three-dimensional (3D) model, to study the thermal performance of single and double U-tube ground-coupled heat pump. The result determined the production of heat exchangers connected to a ground–heat pump.

Oyewola et al. (2022), developed an air-cooled battery thermal management system. An air-cooled temperature management module was developed by coupling a unique heat sink using sink of different pin-fin shapes.

Kulkarni & Hinge (2023) used analytical methods (CFD) for the development and the determination of the optimum weir geometry discharge. Furthermore, the applications of the proposed method from the energy aspect are highlighted.

This study simulates a phenomenon in the natural environment within a laboratory, thereby studying the effect of cooling on the surface of the water. The measurement of velocity fields helps in the study of the mechanism of transfer of nutrients within an aquatic recipient, as well as to estimate the length of transport of a polluting load in an aquatic recipient.

According to the above research, there are few studies similar like the present work. Related reports focus mainly on a field study in natural receivers and on the development of mathematical models investigating water quality, heat transfer in open channels and thermal pollution. The present research focus on the effect of the cooling load on a water receiver and can be used in conjunction with other studies on issues of environmental interest, such as the determination of the transport of a pollutant load in a water receiver, as well as locating the correct water intake location from a water receiver so that high-temperature water is not drained.

2. MATERIALS AND METHODS

2.1. Experimental Setup

When a cooling load is applied to the water surface of a basin area T1, then mass transfer is observed in the rest of the basin T2 (Fig. 1). The effect of this cooling load is studied in the laboratory.

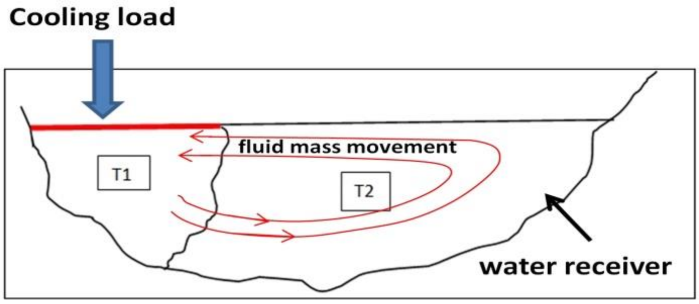

Fig. 1 Water mass of fluid with different temperature ranges

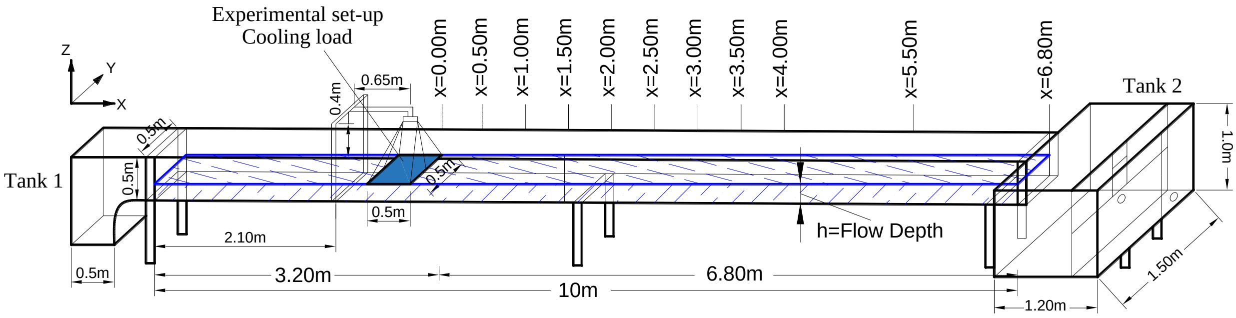

Fig. 2 Open channel and the location of the experimental set-up

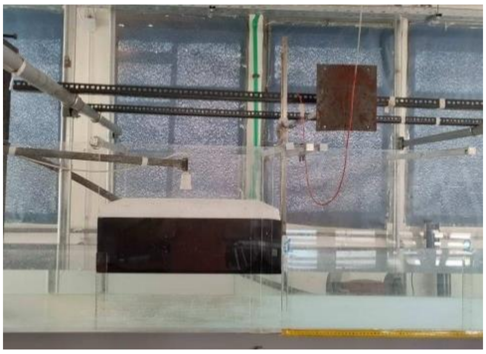

Fig. 3 Experimental device

Fig. 4 Cooling load inside the device

The study of the effect of cooling load on a water surface (Fig. 8) was carried out at the Hydraulics Laboratory of the Department of Environmental Engineering of the International University of Greece (IHU).

The experiments were conducted in an open channel of 10 m in length, 50 cm in width, and a height of 50 cm (Fig. 2). The experimental set-up was placed in an area 2.70 m to 3.20 m from the entrance of the channel, with a free measurement length of 6.80 m. The bed slope of the channel was kept constant and equal to 0.00 in all experiments. The phenomenon is created from both directions of the experimental set-up. Figure 2 also shows the cross-sections (plane Z) along the X axis, where the temperature field was measured starting at X=0.00 m to 6.80 m.

The ambient temperature did not change over time during the experimental procedure, and thus, the results were not affected. Also, the bed friction of the channel and the motion of the fluid were considered negligible because the velocities were very low during the experimental procedure.

The experimental cooling device was made by metal, with dimensions of 50 cm X 50 cm and a height of 15 cm and supported by wire on vertical metal shafts. Insulating material was placed on all sides of the box except for the bed, to prevent the cargo from escaping into the environment. The device was placed directly on the surface of the water so that transfer of the cooling load through convection could be successfully achieved (Fig. 3, 4).

2.2. Experimental Measurements

An initial measurement of the water density for different temperatures was carried out. The above measurements were taken in a set of insulating containers with a capacity of 500 ml (Fig. 5.1, 5.2) containing a mixture of hot and cold water to achieve a range of temperature values. Figure 11 shows the density-

Fig. 5.1 Density device

Fig. 5.2 Densitometer

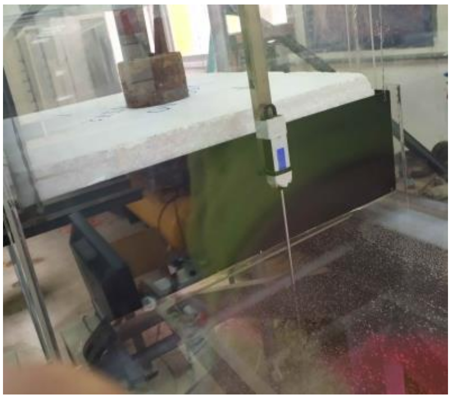

Fig. 6 Temperature measurement

temperature diagram, from which the equation 1 for the relationship between density (ρ) and temperature (T) was derived.

Thermal losses are reduced to a minimum when the measurements are conducted so that temperature does not change during the time they are carried out. Measurement errors are minimized because, at the time of the density calculations, the temperature values were constant due to the fact that there are hardly any losses to the environment thanks to the insulation of the device.

The open channel was filled with water with different flow depths in each case (5, 10, 15, and 20cm). Five (5) experiments for each flow depth were carried out with different cooling loads. The value of the cooling load was achieved with the help of insulating films at the bottom of

Fig. 7 Insulating bottom film with gap

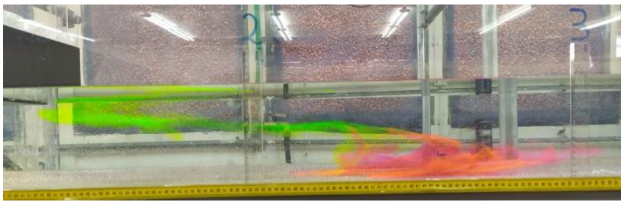

Fig. 8 Rhodamine in the cooling experiment

the experimental device. The insulating films had a different opening for each experiment, (gap - D) with a width of 50 cm (Y axis) and along the X axis from 2 cm to 26 cm (Fig. 7). This gap (D) allowed the cooling load to pass through the water.

The parameters that examined were the flow depth at 5/10/15/20 cm and the values of the temperature field that were developed under the influence of the cooling load. Specific sets of parameters were selected in the implementation of the experiments. The sensitivity of measurements corresponded to the sensitivity of the measuring instrument.

The temperature field was measured using a waterproof digital thermometer (Fig. 6). The diagrams of the isothermal curves were obtained (Fig. 12). For each flow depth, the temperature measurement points on the vertical Z axis are shown in Fig. 10.1 to 10.4.

Finally, the average field of velocities (Fig. 13) was measured by the rhodamine dye spillage in a known location, with the measurement of the dye in space and time. The motion of the dye was recorded using a digital camera (Fig. 9).

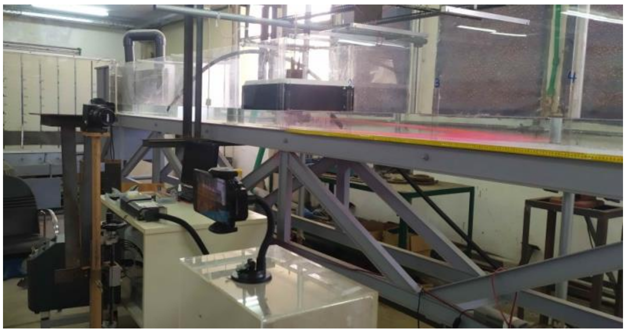

Fig. 9 Rhodamine video recording device

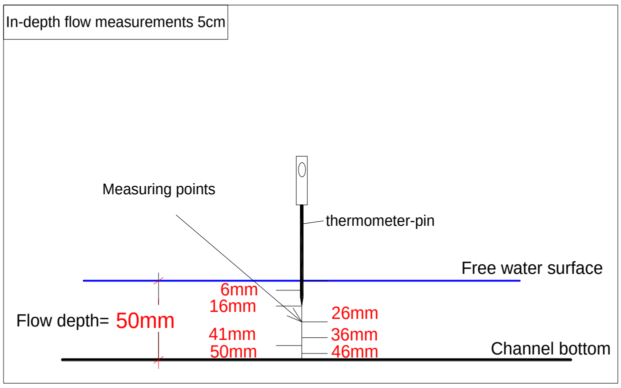

Fig. 10.1 Measurement positions on Z-axis depth 5 cm

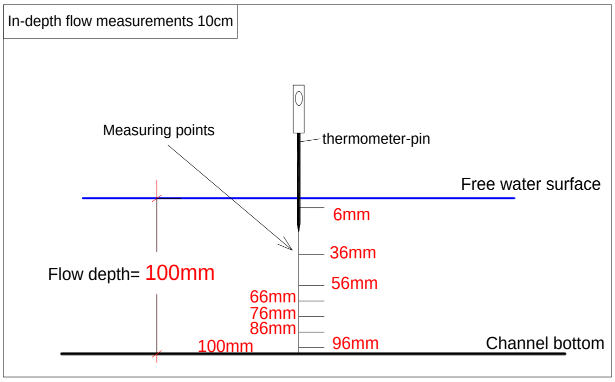

Fig. 10.2 Measurement positions on Z-axis depth 10cm

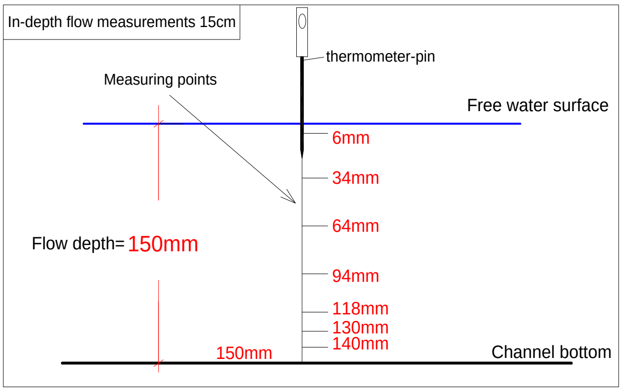

Fig. 10.3 Measurement positions on Z-axis depth 15cm

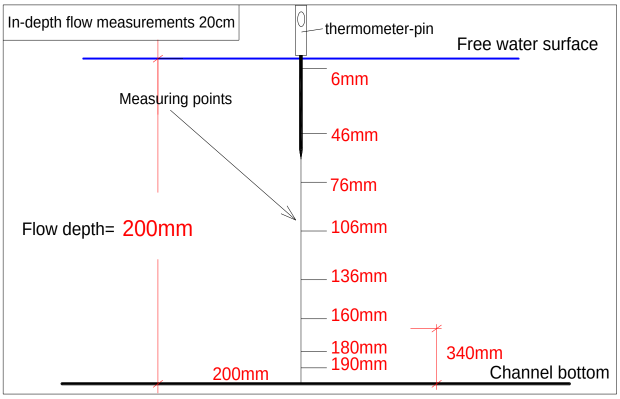

Fig. 10.4 Measurement positions on Z-axis depth 20cm

Table 1 Values of supply water density

Tank	Tempe-rature °C	density ρ gr/cm^3	Tank	Temp. °C	density ρ gr/cm^3
measur 1	17.2	0.9975	measure 5	20.2	0.9970
measur 2	17.6	0.9975	measure 6	21.2	0.9965
measur 3	18.0	0.9975	measure 7	22.4	0.9965
measur 4	19.1	0.9970	measure 8	23.6	0.9960
measur 9	17.7	0.9975	measure 13	10.2	0.9990
measur 10	16.1	0.9985	measure 14	8.5	0.9995
measur 11	14.1	0.9985	measure 15	5.8	1.0000
measur 12	12.4	0.9990	measure 16	4.4	1.0000

The purpose of this study was the calculation of mass transport of the cooled mass (cooling transfer) in the rest of the still water mass in relation to the temperature variation and the flow depth along the channel. The field of average velocities is shaped by the difference in densities, which is caused by the temperature variation in the fluid mass. The measurements are taken when thermal equilibrium is achieved (steady phenomenon), i.e., when the amount of cooling load is constant and there are no other changes of temperature values in the fluid mass.

3. MEASUREMENTS

In this unit the experimental results of Leousidis et al. (2022), conducted in a laboratory open channel, are presented. More specifically, the water density measurements are presented in the following table (Table 1):

The density-temperature diagram is obtained from Table 1:

Following the diagram in Fig.11, the relationship between density (ρ) and temperature (T) is:

$$\rho = -0.00022 \times T + 1.0013 \qquad (1)$$

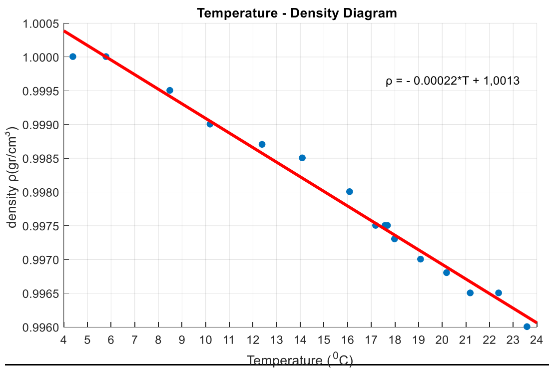

Fig. 11 Density – temperature diagram

Subsequently, the temperature field was measured in vertical cross-section along the X-axis of the channel, and the following diagrams (Fig.12.1 to 12.20) were obtained for flow depth of 5/10/15/20 cm.

Flow Depth h=20 cm

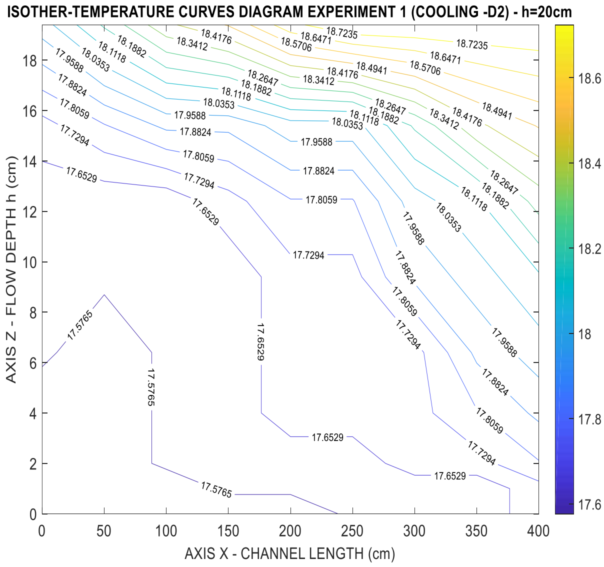

Fig. 12.1 Depth h=20cm, exp.1

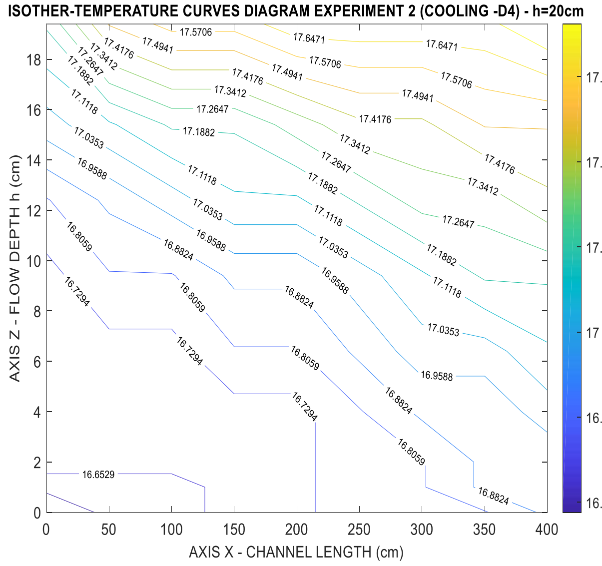

Fig. 12.2 Depth h=20cm, exp.2

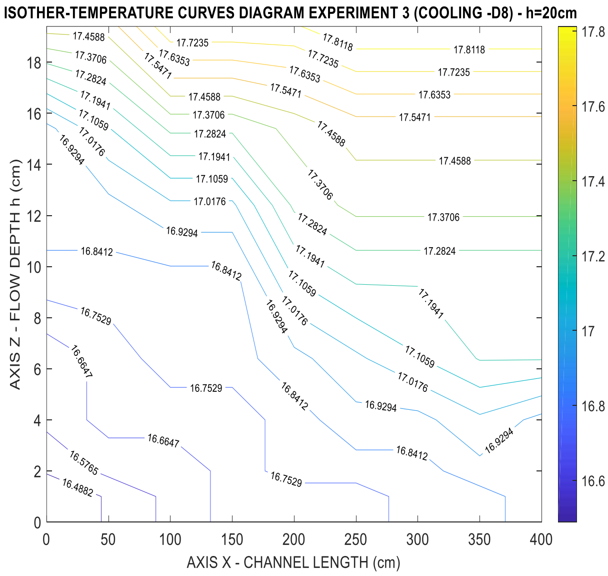

Fig. 12.3 Depth h=20cm, exp.3

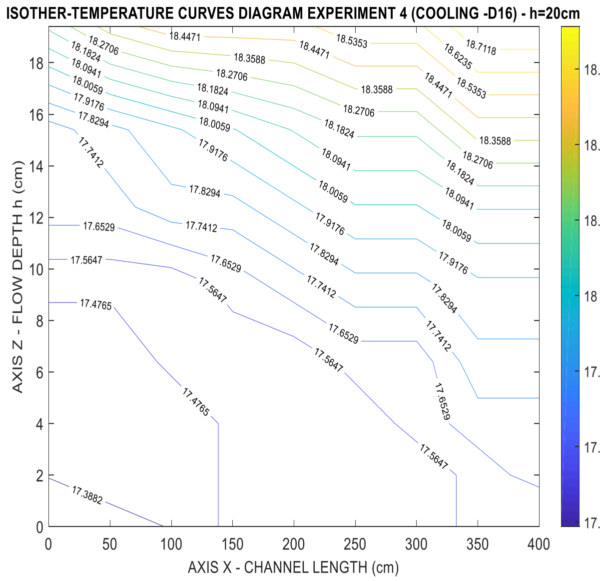

Fig. 12.4 Depth h=20cm, exp.4

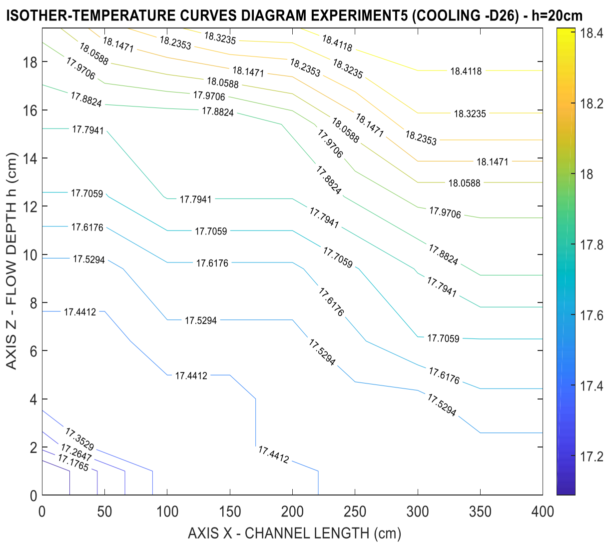

Fig. 12.5 Depth h=20cm, exp.5

Flow Depth h=15 cm

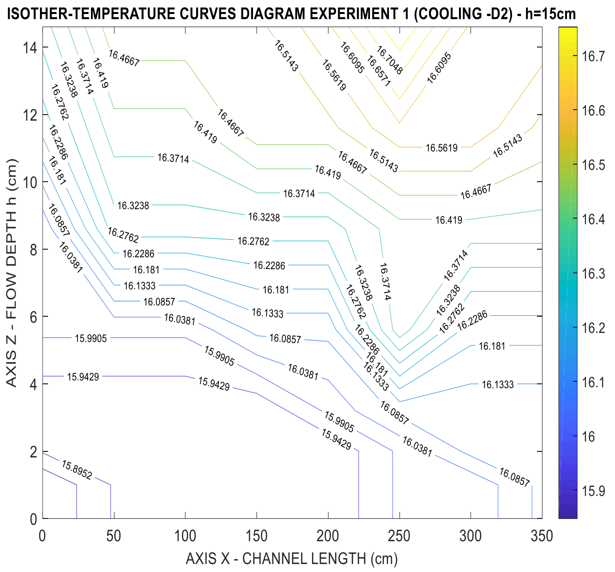

Fig. 12.6 Depth h=15cm, exp.1

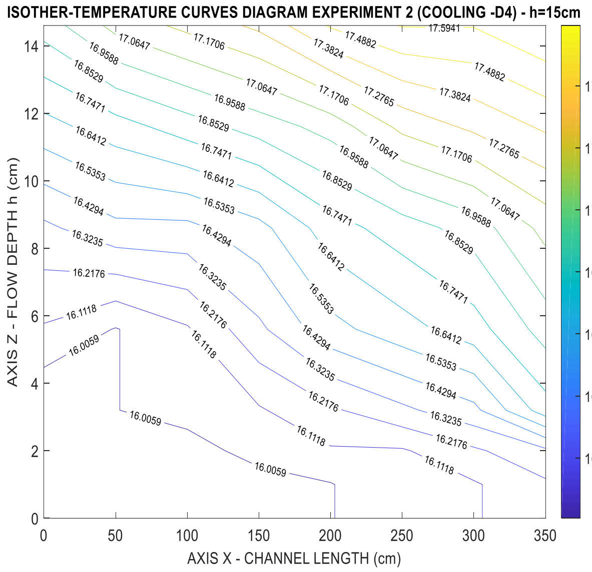

Fig. 12.7 Depth h=15cm, exp.2

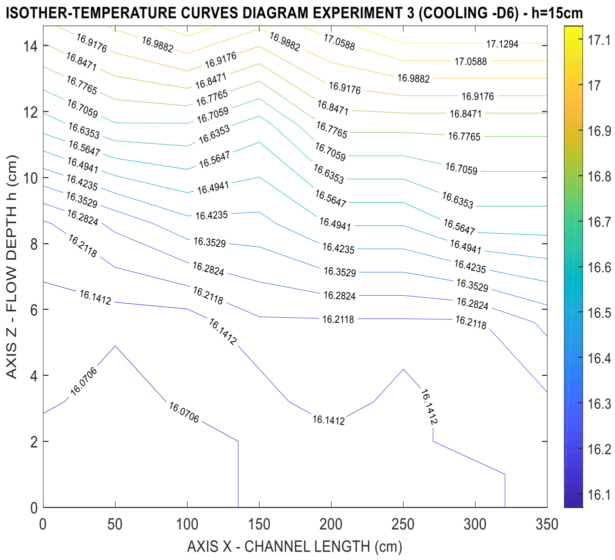

Fig. 12.8 Depth h=15cm, exp.3

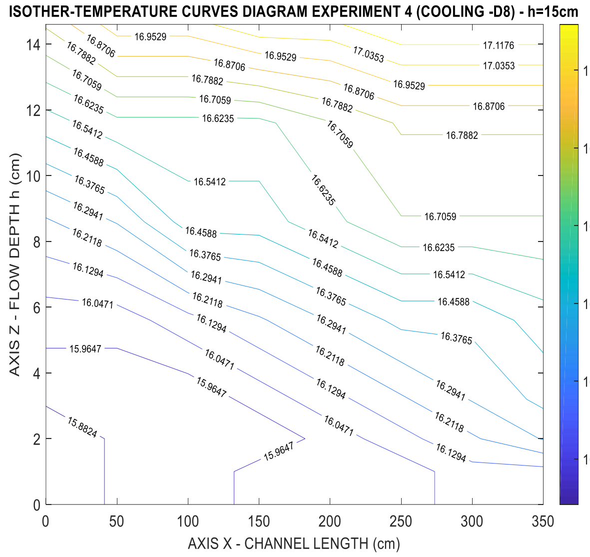

Fig. 12.9 Depth h=15cm, exp.4

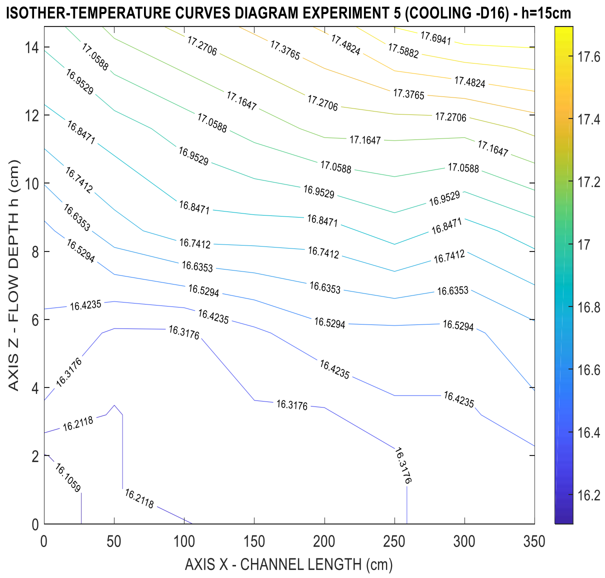

Fig. 12.10 Depth h=15cm, exp.5

Flow Depth h=10 cm

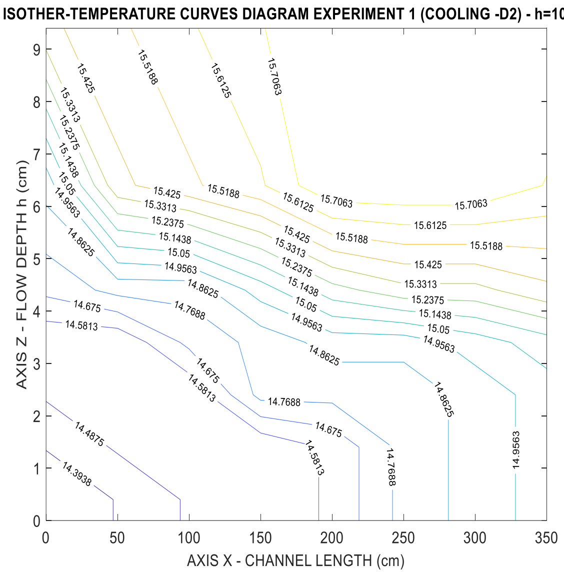

Fig. 12.11 Depth h=10cm, exp.1

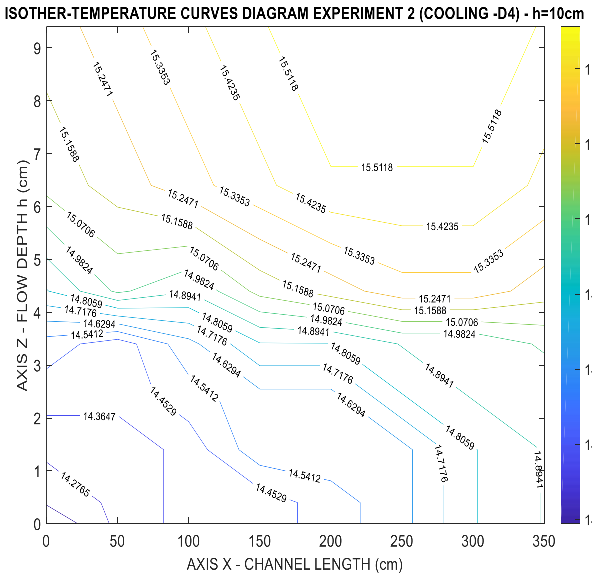

Fig. 12.12 Depth h=10cm, exp.2

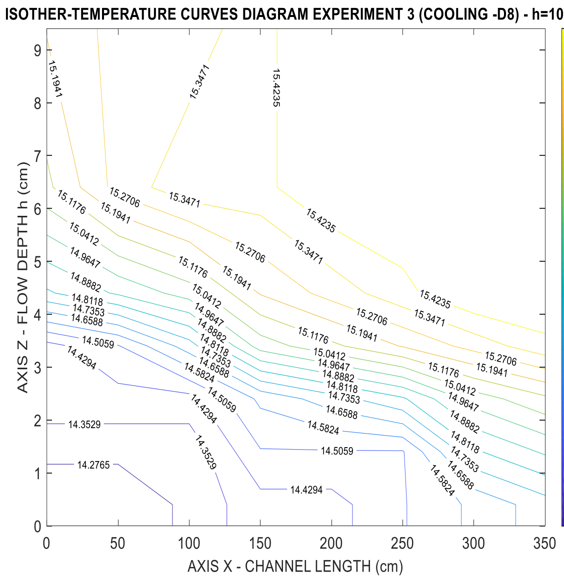

Fig. 12.13 Depth h=10cm, exp.3

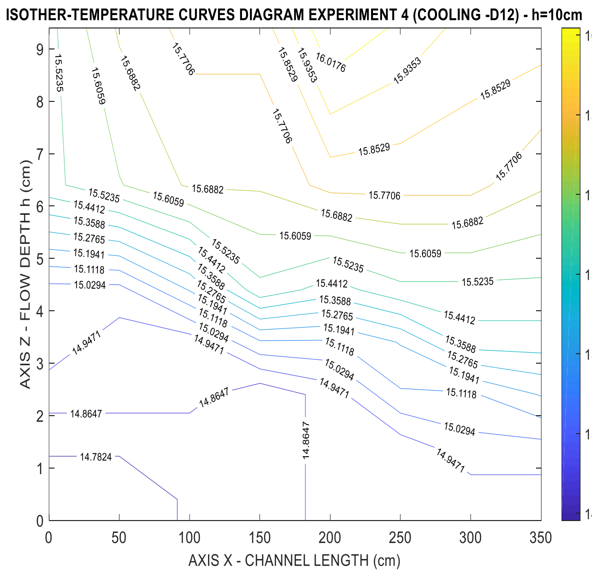

Fig. 12.14 Depth h=10cm, exp.4

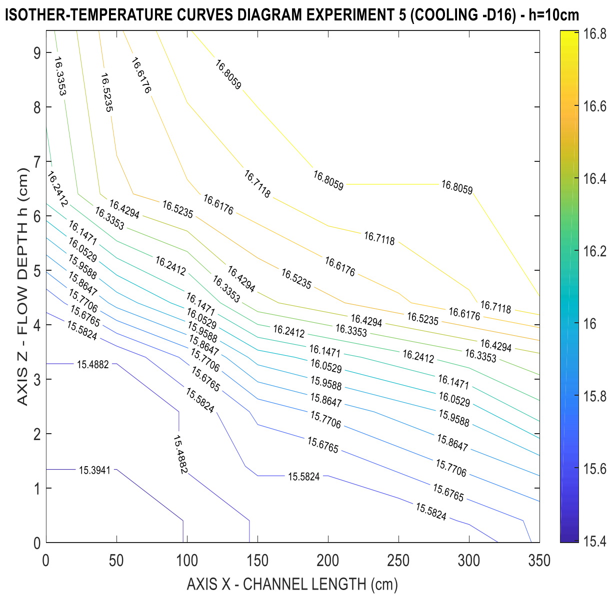

Fig. 12.15 Depth h=10cm, exp.5

Flow Depth h=5 cm

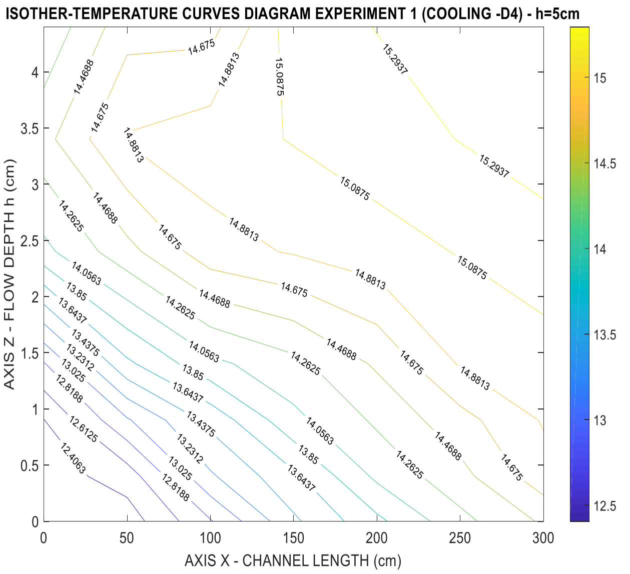

Fig. 12.16 Depth h=5cm, exp.1

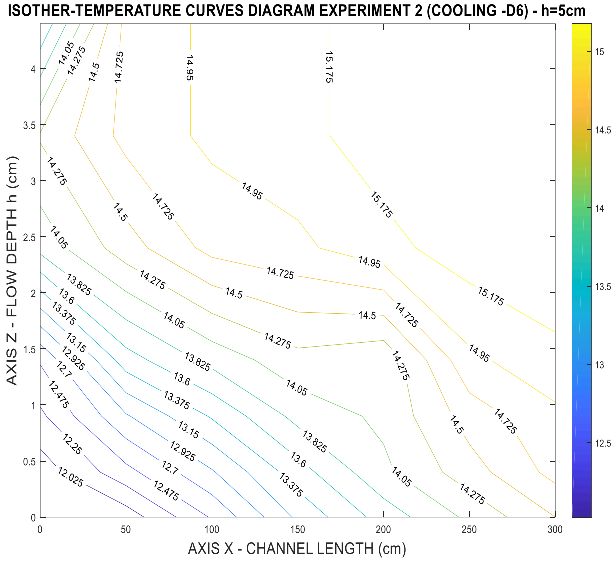

Fig. 12.17 Depth h=5cm, exp.2

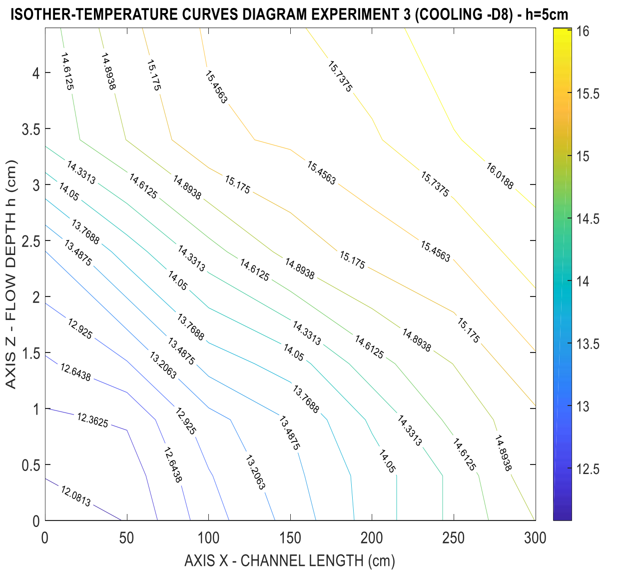

Fig. 12.18 Depth h=5cm, exp.3

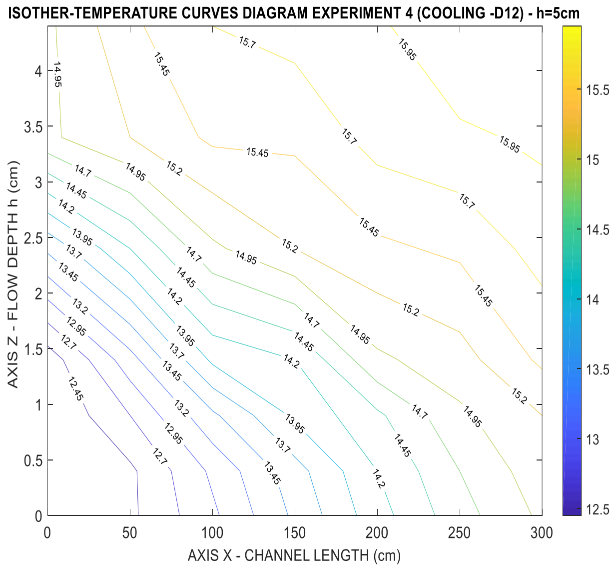

Fig. 12.19 Depth h=5cm, exp.4

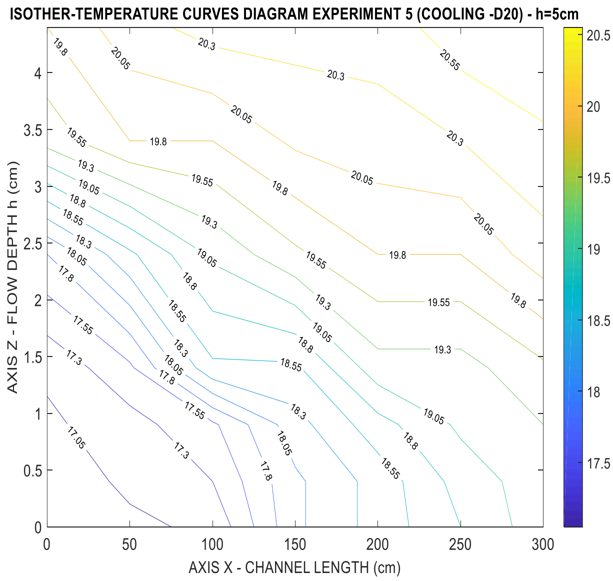

Fig. 12.20 Depth h=5cm, exp.5

The above diagrams of isotherm curves show the motion of the cold mass from the place of application of the cooling load and the drop of the curves towards the bed of the channel. When isothermal curves are parallel to the channel bed (X-axis), a loss of zero cooling load is observed. The cold mass of water was appeared at the channel bed due to the decrease in the density of the water elements.

The velocity field was measured by recording the motion of the dye along the channel (X-axis), using a digital camera. The diagrams are shown in Fig.13.1 to 13.4.

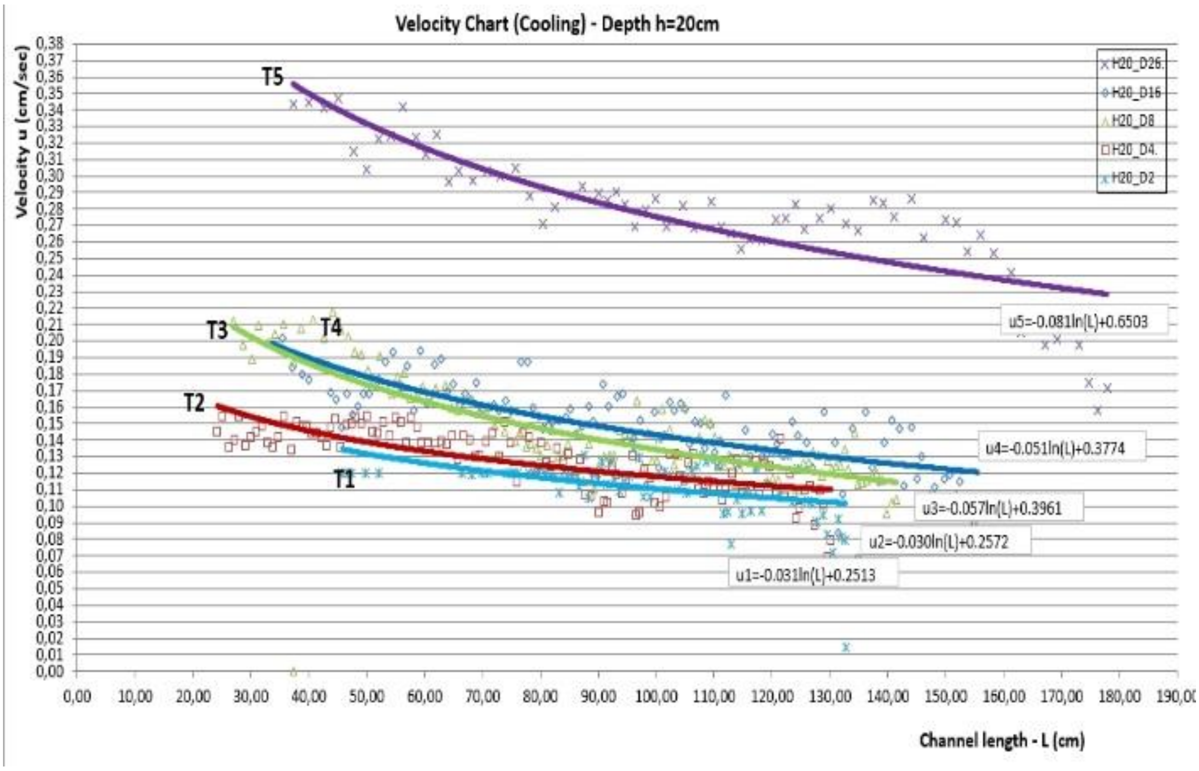

Fig. 13.1 Mean velocity fields u (cm/sec) on the channel axis (X) for h = 20 cm

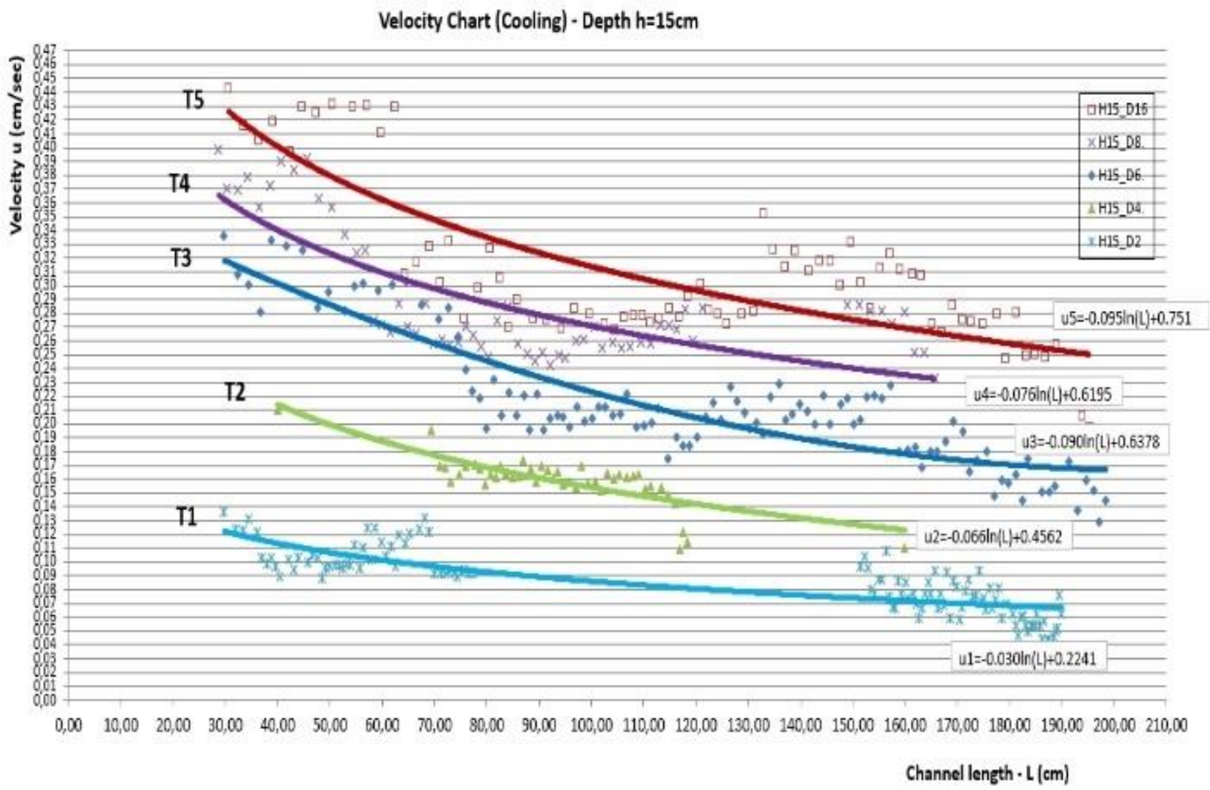

Fig. 13.2 Mean cooling velocity fields u (cm/sec) on the channel axis (X) for h = 15 cm

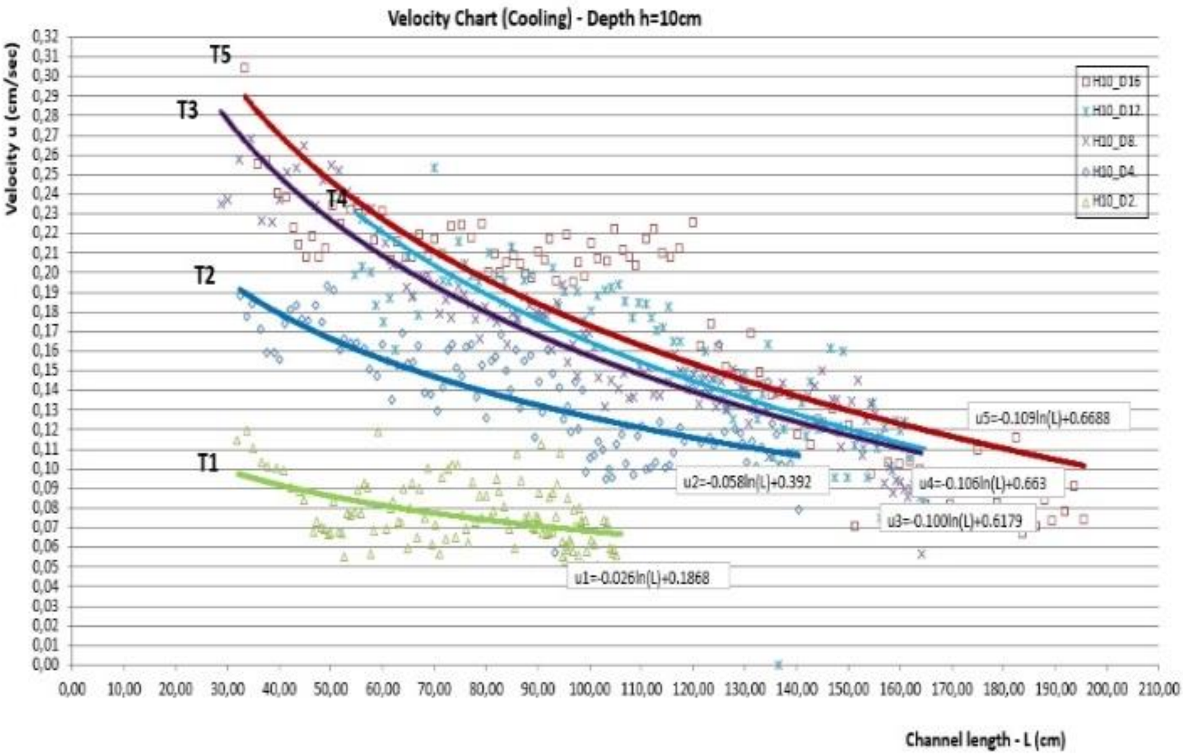

Fig. 13.3 Mean velocity fields u (cm/sec) on the channel axis (X) for h = 10 cm.

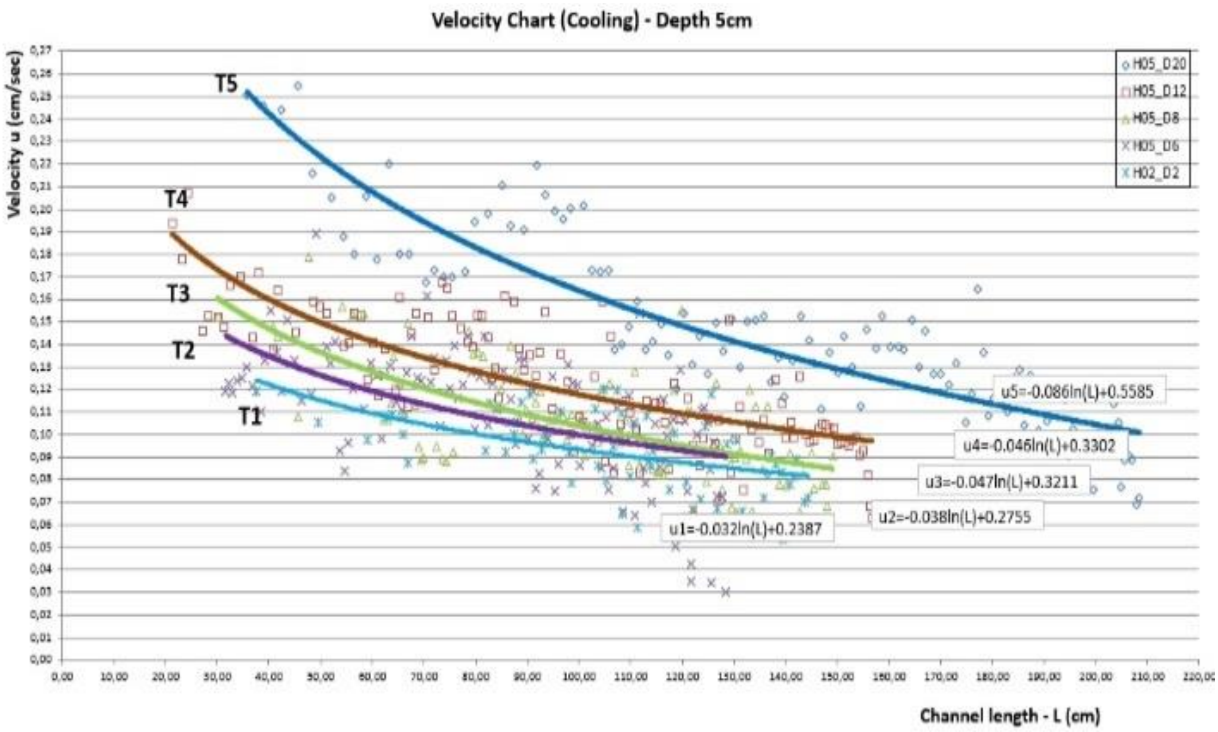

Fig. 13.4 Mean velocity fields u (cm/sec) on the channel axis (X) for h = 5 cm.

The diagrams of the velocities indicate that when the values vary between 0 and 0.05 cm/s, diffusion prevails over the transport. As for the velocities that developed at a low flow depth, such as 5 cm, there was a more irregular course of values compared to those of the other flow depths. That happened because the ambient temperature has a stronger effect on the smaller mass of water.

4. RESULTS

The equations of velocities u (cm/sec) for each flow depth under the influence of the cooling load are taken from the diagrams (Fig.13) and presented in Table 2:

Table 2 Mean velocity equations under the influence of cooling load

depth	equation	ΔT
20cm	u_1=-0.031ln(L)+0.2513	15.0
20cm	u_2=-0.030ln(L)+0.2572	15.5
20cm	u_3=-0.057ln(L)+0.3961	15.8
20cm	u_4=-0.051ln(L)+0.3774	16.0
20cm	u_5=-0.081ln(L)+0.6503	16.2
15cm	u_1=-0.030ln(L)+0.2241	8.0
15cm	u_2=-0.066ln(L)+0.4562	9.2
15cm	u_3=-0.090ln(L)+0.6378	9.8
15cm	u_4=-0.076ln(L)+0.6195	10.0
15cm	u_5=-0.095ln(L)+0.7510	10.0
10cm	u_1=-0.026ln(L)+0.1868	4.9
10cm	u_2=-0.058ln(L)+0.3920	5.0
10cm	u_3=-0.100ln(L)+0.6179	5.2
10cm	u_4=-0.106ln(L)+0.6630	4.8
10cm	u_5=-0.109ln(L)+0.6688	4.9
5cm	u_1=-0.032ln(L)+0.2387	2.3
5cm	u_2=-0.038ln(L)+0.2755	2.3
5cm	u_3=-0.047ln(L)+0.3211	2.6
5cm	u_4=-0.046ln(L)+0.3302	3.0
5cm	u_5=-0.086ln(L)+0.5585	2.2

Table 3 Temperature changes and cooling wedge

cool transfer	Flow depth (cm)	Initial water temperature T_v (^{0}C)	cooling equilibrium temperature T_o the position X=0.0cm (^{0}C)	ΔT (T_o-T_v) (^{0}C)	Experiment cold wedge length L (cm)	b – Cold mass thickness in place X=0.00 (cm)
exp1	20	17.8	17.5	-0.3	450	15.0
exp2	20	17.0	16.5	-0.5	540	15.5
exp3	20	17.2	16.4	-0.8	610	15.8
exp4	20	18.2	17.3	-0.9	680	16.0
exp5	20	18.0	17.0	-1.0	680	16.2
exp1	15	16.2	15.8	-0.4	420	8.0
exp2	15	16.4	15.9	-0.5	500	9.2
exp3	15	16.6	16.0	-0.6	580	9.8
exp4	15	16.5	15.8	-0.7	620	10.0
exp5	15	16.8	16.0	-0.8	680	10.0
exp1	10	15.5	14.3	-1.2	630	4.9
exp2	10	15.5	14.2	-1.3	650	5.0
exp3	10	15.6	14.2	-1.4	680	5.2
exp4	10	15.7	14.7	-1.0	600	4.8
exp5	10	16.4	15.3	-1.1	620	4.9
exp1	5	15.1	12.1	-2.9	450	2.3
exp2	5	15.0	11.8	-3.2	620	2.3
exp3	5	15.2	11.8	-3.4	680	2.6
exp4	5	15.5	12.2	-3.3	630	3.0
exp5	5	19.4	16.8	-2.6	400	2.2

The following table (Table 3) presents the values of initial temperature T_v for each flow depth (without the effect of cooling load), the temperature T_v, in which thermal equilibrium prevails, the transport length L of the cold mass of water and the thickness b of the cold mass at the initial measurement position of the temperature field X=0.0 cm. The elements of the table were obtained from the diagrams of the isothermal curves (Fig.12) along with those of the velocity diagrams (Fig. 13).

According to the data in the above table (Table 3), the diagram of the cold mass transfer length (L) is obtained due to the effect of the temperature difference $\Delta T = |T_0 - T_v.|$ (Fig. 14).

The linear equations ($y = a \cdot x$) for each flow depth resulting from the above diagram (Fig. 14), allows the determination of the coefficient a. The coefficient "a" determines the slope of the line and shows the effect that

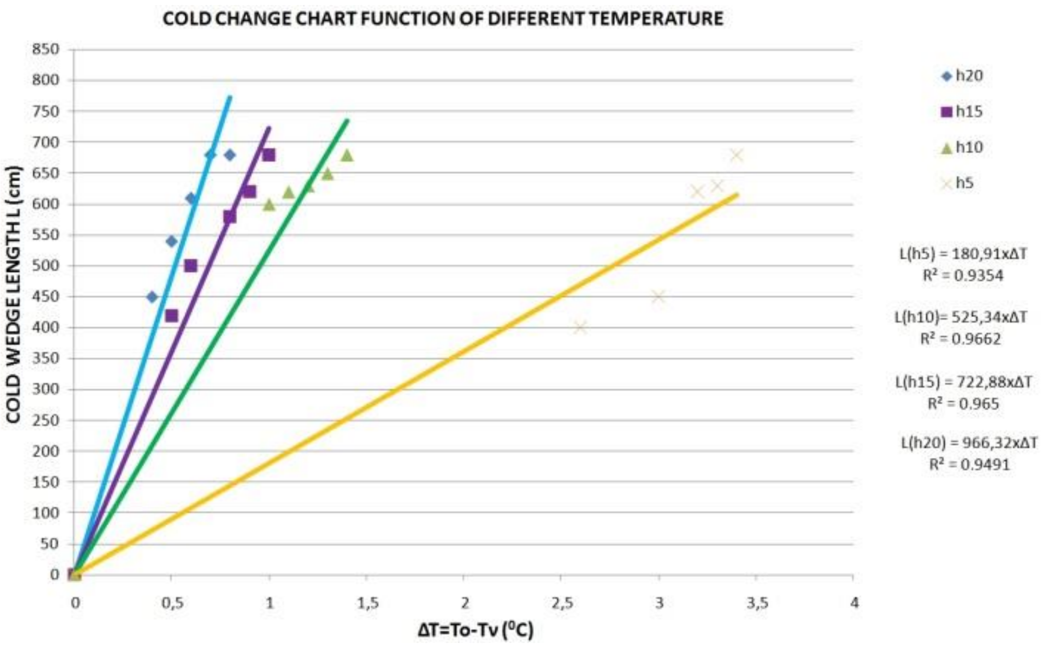

Fig. 14 Cold wedge change diagram as a function of temperature difference

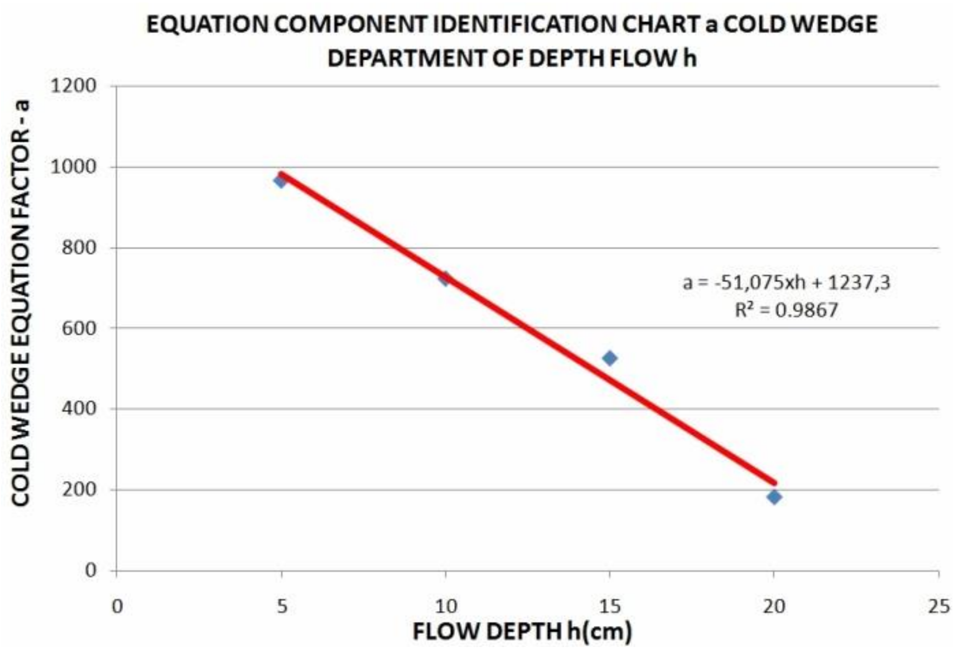

Fig. 15 Equation component identification diagram a cooling wedge department of depth flow

Table 4 Pair of values of depth of flow and coefficient an of cold wedge equation L

Flow depth (cm)	coefficient a
5	180.91
10	525.34
15	722.88
20	966.32

the temperature difference ΔT has on the length of the cold wedge, which is presented in Table 4.

Thus, the a-h diagram is obtained (Fig.15) from Table 4:

If the equation a=-51.075 x h+1237.3 is replaced in the general relationship of the equation of the length of the wedge L=a x ΔT, the final equation (2) is obtained for determining the length of the cold mass as a function of the flow depth, and the temperature difference ΔT, in a state of thermal equilibrium.

The final equation of the length (L) of the cold mass takes the following form:

$$L = (-51.075 \times h + 1237.3) \times \Delta T \quad (2)$$

5. CONCLUSIONS

According to the above results, the number of twenty (20) experiments carried our) is capable of accurately estimating equation (2) of the transport length of the cold mass as a function of the flow depth and the temperature difference ΔT. In addition, the length of the cold wedge L increases with the larger temperature difference ΔT.

The measurement of the velocity fields was carried out in a two-dimensional velocity field (X–Z axis), considering that there was a uniform cooling load along the Y axis (channel width).

The diagrams of isothermal curves under the influence of cooling (Fig. 12.1 to 12.20), indicate that the isothermal curves are developed at the bottom of the channel due to the increase in the density of the water. In the cases where the isothermal curves show a parallel trend to the axis of the channel, water temperatures are not affected by the cooling load, so the fluid temperature was the same with the temperature of the surrounding environment. The diagrams of the isothermal curves follow the net heat flow due to cooling that occurs at the front of the cooled region, where the water mass starts to flow. The thickness of the cold mass can also be determined.

The motion of the cold mass was downward due to the higher density compared with the density of the surrounding fluid. Due to the existence of the bed, there was also a lateral motion, which was appeared with the form of a wedge, just as expected. Therefore, the wedge length, that will be developed, depends on the depth, the density of the surrounding fluid and the cooling load density.

The wedge length equations are given as a function of depth h and temperature difference ΔT. This is an important tool to estimate the total motion of the cooling load.

From the above velocity equations, the mean velocity for various flow depths was determined as a function of the final length L of the wedge for different ΔT. The experiments were also verified by a mathematical model Leousidis (2022).

In this research an essential, daily natural phenomenon (the effect of cooling load on water systems) within the laboratory was studied. The results of this research lead to the determination of the length of water mass transfer under the influence of a cooling load.

The results of this study are summarized in the following points:

i. the findings of the present research can be implemented in a water basin for water supply use of an area. The knowledge of the water placement is crucial, so that high-temperature water is not drained,

ii. the maximum length of the hot or cold mass can be determined in hot or cold liquid masses discharged to a receiver,

iii. the knowledge of the depth variation of the water temperature of a cooled basin from low atmospheric temperatures is important,

iv. in the study of liquid waste pollutant dispersion in water receivers, e.g., lakes, seas, etc.

v. the water temperature is a determining factor for studying a freshwater ecosystem.

The equations for the determination of the mass transport that resulted from the cooling load effect can also be used in research programs in combination with possible other parameters, e.g., study of the motion length of a pollutant load in a water receiver.

Further study of this phenomenon can solve many problems that arise in everyday life. Other parameters that affect the aquatic ecosystem can be examined. More specifically, the equation for the determination of the mass transport resulting from the effect of cooling load can be used in research programs along with other potential parameters such as salinity, vegetation, etc. This could be done to study the motion length of a pollutant load in a water recipient and the determination of the possibility of self-purification.

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CONFLICT OF INTEREST STATEMENT:

On behalf of all authors, the corresponding author states that there is no conflict of interest.

AUTHORS CONTRIBUTION

Alexandros Leousidis: Research Data, Investigation, Visualization, Writing – original draft; **Evangelos Keramaris**: Conceptualization, Data curation, Project administration, Supervision, Writing – review & editing; **George Pechlivanidis**: Conceptualization, Methodology, Project administration, Supervision, Data curation; **Yiannis Savvidis**: Formal analysis, Methodology, Validation, Writing – review & editing.

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