IS PISTON EFFECT KILLED BY CONVECTION ?

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ABSTRACT

This paper answers some recent questions posed by heat propagation mechanisms in near supercritical pure fluids under normal gravity conditions. The role of microgravity experiments in the discovery of a fourth temperature equilibration mode in hypercompressible fluids, named the Piston Effect, is first recalled as well as its basic mechanisms that are responsible for temperature equilibration on a much shorter time scale than heat diffusion. The question whether this mechanism still exists on ground is then approached. The results of the numerical calculations that have permitted to give an answer are presented and the basic references given. It is emphasized in particular on the fact that although Piston Effect has been put in evidence thanks to microgravity experiments, this effect appears to be the heat equilibrating mechanism on ground, leading to the striking evidence of a quasi isothermal convection. Recent modeling in connection with experiments that suggested Piston Effect could be killed by convection shows on the contrary that a cooling Piston Effect, triggered by thermal plumes, prevents the bulk increase in temperature.

KEY WORDS: supercritical fluids, convection, hypercompressible fluids, numerical hydrodynamics, finite volume methods.

1. INTRODUCTION.

The experimental evidence of intense convection in near critical fluids when heated led to interpret the observed fast temperature equilibration process as due to convective transport: this transport mode is the only one remaining since heat diffusivity is vanishing in the vicinity of the critical. This was coherent with the fact that the strength of the observed convection could be explained by the huge density gradients due to the diverging isothermal compressibility. However, at the beginning of the 80's, experiments performed under microgravity conditions suggested the thermalisation process could be very fast even in the quasi convection free environment of space [1], [2]. Several teams then gave an explanation to this observation [3], [4], [5], under the form of the prediction of the existence of a fourth new temperature equilibration mechanism due to a thermoacoustic process we called the Piston Effect. After this mechanism was checked under microgravity conditions [6], [7] and widely admitted, then came the question why should a strong convection exists on ground since temperature is equilibrated: is Piston Effect killed by convection? A negative answer has been given by numerical simulations. In the same way, a very special property of thermogravitational convection in near critical fluids has been put forward, namely the existence of quasi isothermal convection. However, some experiments performed on ground with non adiabatic walls [8] and heat addition from a source led to the impossibility of heating up the bulk. Additional modeling recently showed Piston Effect is not killed but on the contrary is enhanced by thermoacoustic interaction of the thermal plume rising from the source with the thermostated wall. Part one presents general considerations on the Piston Effect; Section 2 is devoted to the study of the Piston Effect heating under normal gravity conditions in

the case of a side-heated square-shaped cavity. Section 3 describes what happens when heat is brought into a cavity from a heat source and focuses on the interaction between a hot plume and the upper thermostated wall.

2. THE PISTON EFFECT.

The question of heat transport in near critical fluids was approached at a workshop on Thermal Equilibration Near the Critical Point organized at NBS by Prof. Moldover under the auspices of NASA in Gathesburg (MA) in March 1989. A set of recent experiments performed under microgravity conditions [1], [2] led to conclude to a possible fast thermal equilibration in near critical fluids under microgravity conditions and needed an explanation. Was this due to remaining convective transport since the Raleigh Number is diverging so that very small g-jitters could homogenize the bulk phase? was this due to a misinterpretation of the specific heats role in the energy balance, or to some adiabatic effect, as proposed by Onuki and Ferrel at the conference, the mechanism of which needed to be identified? Anyway, the question did not get a complete answer at the conference but everybody got back home with the idea something was wrong either with those experiments or with most of the proposed explanations. At that time I just told Daniel Beysens I could perform low Mach number compressible flows calculations so that it could be easy to replace the ideal gas EOS by the van der Waals one and see what happens in a near critical fluids after heating; the use of this EOS, although non exact, was considered to be able to lead to at least a phenomenologically correct description. On the other hand, I just came back at that time from a stay at the Center for Low Gravity Fluid Mechanics and Transport Phenomena of CU at Boulder where I met David Kassoy that initiated me to thermoacoustic asymptotic

techniques and to a negligibly small phenomena in ideal gases he named the Piston Effect in his work [9]. All this led me naturally on the track of the thermoacoustic nature of what came out of the numerical calculations; we were indeed surprised to find that temperature in the bulk was homogeneous and that equilibration was quite completed after some percents of the heat diffusion characteristic time as reported on Fig. 1. This numerical simulation [3] was consistent with the results obtained by our colleagues [4], [5] with the use of totally different methods. More sophisticated multiple time scales analysis [10], then allowed us to give a complete description of the process in term of thermoacoustic: compression waves emitted at the edge of the thermal boundary layer that flash back and forth in the cavity provoke an increase in temperature by adiabatic heating which is much faster than diffusion (see Fig. 2). This is why our colleagues not working with hydrodynamics and acoustics but with more global descriptions [4], [5], named the effect the Adiabatic Effect, since it corresponds indeed to an adiabatic heating of the bulk phase. These first interpretative descriptions have been then followed by asymptotic analysis aiming to get the critical behavior of the hydrodynamic field variables as a function of the distance to the critical point [11], [12],. In the meantime some other striking properties of acoustic wave propagation and reflection have been put forward [13], [14], together with the description of the saturation of the Piston Effect when closer to the critical point than a certain predicted amount [15]. In such situations heat should equilibrate as fast as the speed of sound. (see Fig. 3).

2. IS PISTON EFFECT KILLED BY CONVECTION?: The 2-D cavity problem with side heating and adiabatic walls.

As explained in the introduction, it was natural to see whether heat is equilibrated on ground since strong convective notion is observed, or in other words to answer the question: does Piston Effect still exists in the presence of convection? Some experiments by Gammon and Co-authors [16], reporting heat could be equilibrated very fast on ground and thus in the presence of convection could not in fact give a complete answer to the question : is the fast heat equilibration when observed due convection or to the Piston Effect? This question is of prime importance to the wide majority of scientists working on ground since the understanding of any non isothermal experiment on ground should need the knowledge of the properties of convective motion in hypercompressible fluids. We describe here the main features of the results reported in a recent paper [17], devoted to the most simple situation to consider to this end, namely the side heated square cavity filled with a supercritical fluid set at 1 K above its critical temperature. Other situations involving possible unstable situations, as the Rayleigh-Benard one or Raleigh-Taylor ones for example., are too complex in the perspective of exploring the basic properties of thermogravitational convection in near critical fluids. These situations are currently under study [18] and [19]. The situation that has been already been computer simulated is the following. A square cavity (2-D problem) is filled with $C0_2$ set at 1 K above its critical temperature. The fluid is initially at rest and at the thermodynamic equilibrium. The upper, bottom and right hand side boundaries are adiabatic. The temperature of the left hand side boundary is then increased linearly of 10 mK in 1 s and then kept constant. The simulation consists in solving the 2-D unsteady Navier Stokes equations in order to study the transient between the initial and the final equilibrium temperatures in the cavity. These equations are written for a Newtonian

viscous and heat conducting van der Waals gas.The governing equations thus write under the following form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \qquad (1)$$

$$\frac{D(\rho \mathbf{v})}{Dt} = -\gamma^{-1} \nabla P + \varepsilon \left[\nabla^2 \mathbf{v} + \frac{1}{3} \nabla (\nabla \cdot \mathbf{v}) \right] + \frac{1}{F_r} \rho \mathbf{g} \qquad (2)$$

$$\frac{D(\rho T)}{Dt} = -(\gamma - 1)(P + a\rho^2)(\nabla \cdot v) \frac{\varepsilon \gamma}{P_r} \nabla \cdot [\lambda \nabla T] + \Phi \qquad (3)$$

Where $\Phi = \varepsilon \gamma (\gamma - 1) \left[v_{i,j} v_{j,i} + v_{i,j} v_{i,j} - \frac{2}{3} v_{i,i} v_{j,j} \right]$ is the viscous dissipation rate, ε is a small parameter defined by $\varepsilon = P_r t_a^{'} / t_d^{'}$ where $t_d^{'}$ is the characteristic heat diffusion time for the ideal gas and $t_a^{'}$ the characteristic time of acoustic phenomena. The quantity P_r is the Prandtl number for an ideal gas and F_r the acoustic Froude number. The following transport coefficient are considered:

$$\lambda = 1 + \Lambda (T - 1)^{-0.5}; \quad C_v = 1; \quad \tilde{\mu} = 1$$

where λ, C_v et $\tilde{\mu}$ are respectively the heat conductivity, the specific heat at constant volume and the dynamical viscosity reported to their ideal gas value. Those expression of course do not describe the real critical behavior of a critical fluid but correspond to a mean field theory which is correct enough to study phenomenology and not to perform quantitative comparisons with experimental results.

The van der Waals equation write under the following non dimensional form:

$$P = \frac{\rho T}{1 - b\rho} - a\rho^2 \qquad (4)$$

where a=9/8 et b=1/3 are given by the expression of the critical coordinates.

The fluids is initially at rest and the stratification is neglected since the distance to the critical point is not smaller than 1 K.

As explained in Ref. [17], the van der Walls EOS is used, and the reasons are the same as those considered for the transport coefficients. The governing aquatints are discretized

on a non uniform staggered mesh by means of a finite volume method; the obtained equations are then solved by a SIMPLE-type algorithm [20] associated with an acoustic filtering procedure. [21].

2.1 PISTON EFFECT IS NOT KILLED BY CONVECTION.

Fig. 4 plots the temperature field at t= 4.5 s after heating has been stopped. We observe that temperature equilibrium in the cavity is almost achieved through the PE, while the effect of buoyancy is restricted to a low-density thermal plume visible at the hot wall and top-left part of the cavity. The perfect gas thermal field which is shown on Fig. 5 for the same time and heating conditions is inhomogeneous because of the larger thermal diffusion coefficient together with weak convection. The homogeneous temperature field in the bulk at a time much shorter than the thermal-diffusion time (Fig. 4) is the signature of the PE and shows that there is no significant interaction between the buoyant convection and the PE. This comes from the fact that the strong upward velocity near the heated wall is parallel to the isotherms and thus does not affects the thermal structure of the thermal boundary layer and thus that of the PE. Figures 6 and 7 show the convective motion at t=4.5 s after heating is stopped in supercritical CO_2 and in CO_2 when an ideal gas. The difference in the structure as well as in the of the convective motion are evident.

2.2. THE ISOTHERMAL CONVECTION

When temperature has been quite homogenized by PE, the remaining temperature gradients diffuse very slowly on the very long diffusive time scale. Due to the very large compressibility, the associated density gradients are still 6.10^3 than those in the perfect

gas. This means that as time goes by, a convective motion fills the cavity which is quite thermally homogenized. For example, at t=713 s, the velocity field plotted in Fig. 8 shows that its magnitude is still 10 times larger than its maximum value in the perfect gas (t = 4.5 s, 6.5 μm/s).although temperature is homogenized by more than 99%.

2.3. A REMARKABLE PROPERTY OF ISOTHERMAL CONVECTION.

Fig. 7 shows a secondary roll is appearing in the left upper corner of the cavity. This is due to an overheating of the top wall which is a consequence of a very unusual phenomena at so low velocities. What happens is that the fluid is accelerated during the rise along the heated wall and its kinetic energy thus increases. When it reaches the upper wall, the direction of the velocity changes from vertical to horizontal and there is thus a point where the velocity is zero: at that point, the kinetic energy that has been « pumped » into the gravity field is turned into internal energy to satisfy the conservation of energy, thus provoking an increase in temperature. Known as the stagnation point effect in normally compressible fluids, this effect to be noticeable needs high velocity flows (higher than Mach number 0.8) so that the kinetic energy and the internal energy have the same orders of magnitude. In normally compressible fluids, usual convective motions are not fast enough so that the increase in kinetic energy is negligible and the effect thus non noticeable. In supercompressible fluids, the increase in internal energy by diffusion through the thermal boundary layer is of the same order of magnitude as the increase in kinetic energy gained during the rise along the heated wall. This effect is thus noticeable in the present situation: the heated wall is colder than the bulk thus provoking a downward flow corresponding to the secondary roll that increases in size as time goes by. (see Fig 8). This points out the very important role of compressibility in driving the

structure of convective flows in supercritical fluids. Considering the formidable difference that exists in such simple situation as presently studied one can imagine the important role played by compressibility in near critical fluids instabilities

3. CAN PISTON EFFECT BE KILLED IN OTHER CONFIGURATIONS?: the heat source problem with an isothermal wall.

As suggested by experiments by Beysens and Collaborators, PE seems not to operate when heat is brought through an immersed thermistor and when the upper wall is thermostated. We have recently performed a numerical experiment based on the same numerical code : a heat flux is set at the central mesh node while the upper wall of the square cavity is maintained at its initial temperature. The result of the simulation is consistent with the observation in the experiment: after an initial increase, the bulk temperature stops increasing to reach a constant value although heat is continuously brought through the thermistor (Fig. 9). The mechanism that has been put in evidence here is the thermoacoustic interaction between the hot plume rising from the thermistor and the upper thermostated wall. A perfect correlation has been demonstrated between the thermal evolution and the hydrodynamic events occurring in the vicinity of the upper wall the mechanism of which has been analyzed and can be summarized as follows. The hot plume flows upward, and brings with it the thermal field since the convective transport is intense. When this hot fluid impinges the upper wall (see Fig. 10), a thin thermal boundary layer forms when the plume interacts with the wall. The fluid contained in that layer contracts and provokes the enhancement of the cooling PE.(the cooling PE corresponds to the propagation of expansion waves in the bulk while the heating PE corresponds to compression waves): this corresponds to the first decrease of the overall

PE heating rate of the bulk phase. (see Fig. 9). The second one is due to the interaction with the upper wall of hot bubbles that had been first convected downward by the vortex flow. This matter is developed in the details in [22]. Accordingly, the Piston Effect is not killed by convection but a different balance between the heating and cooling Piston Effects have been caused by the thermal plume. Before the thermal plume reaches the upper boundary, the resulting temperature evolution is the same as at microgravity conditions. Since the cooling PE has been enhanced alone, the heating one is quite balanced and the bulk increase in temperature no longer possible.

These studies show that it is most likely the thermoacoustic heating of a bulk phase still occurs in most of the ground situations and not only under microgravity conditions where it has been first put in evidence. The complexity of the flow fields and the richness of the encountered hydrodynamic phenomena may suggest the critical phenomena and hydrodynamics communities will find there a wide field of common interest. This seems to be proved by the study of the unstable configurations of Rayleigh-Benard and Rayleigh-Taylor convection in near critical fluids, [19], [22].

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FIGURE CAPTIONS

Fig. 1: Temperature in a 10 mm 1-D slot for different times expressed in % of the heat diffusion time. (T_C + 1K, critical pressure).(from Ref. 2).

Fig. 2 : Two times-scales asymptotic solution showing the heating of the bulk by acoutic wave propagation.(From Ref. 6).

Fig. 3 : Heat equilibration time as a function of the reduced distance μ to the critical point. (ε is the ratio of the acoustic characteristic time to the heat diffusion characteristic time for an ideal gas) (from Ref. 11).

Fig. 4 : The temperature field (K) in a side heated (left hand wall) square cavity 4.5 s after a 1mK increase in temperature has been completed.

Fig 5 : The temperature field (K) at the same time as on Fig. 4 and under the same conditions in a ideal gas.

Fig 6: The velocity field in the cavity (the max vector plot is 2.24 10^2 μm/s), 4,5 s after a 1mK increase in temperature has been completed.

Fig. 7 : The velocity field at the same as on Fig.6 and under the same conditions in an ideal gas (the max. vector is 6.5 μm/s).

Fig. 8 : The isothermal convection : velocity field 713 s after the heating has been stopped. (the max. vector plot is 86 μm/s)

Fig 9 : The bulk temperature evolution as a function of time showing the different changes in the heating rate by Piston Effect.

Fig 10 : The first interaction of the hot plume with the upper thermostated wall.

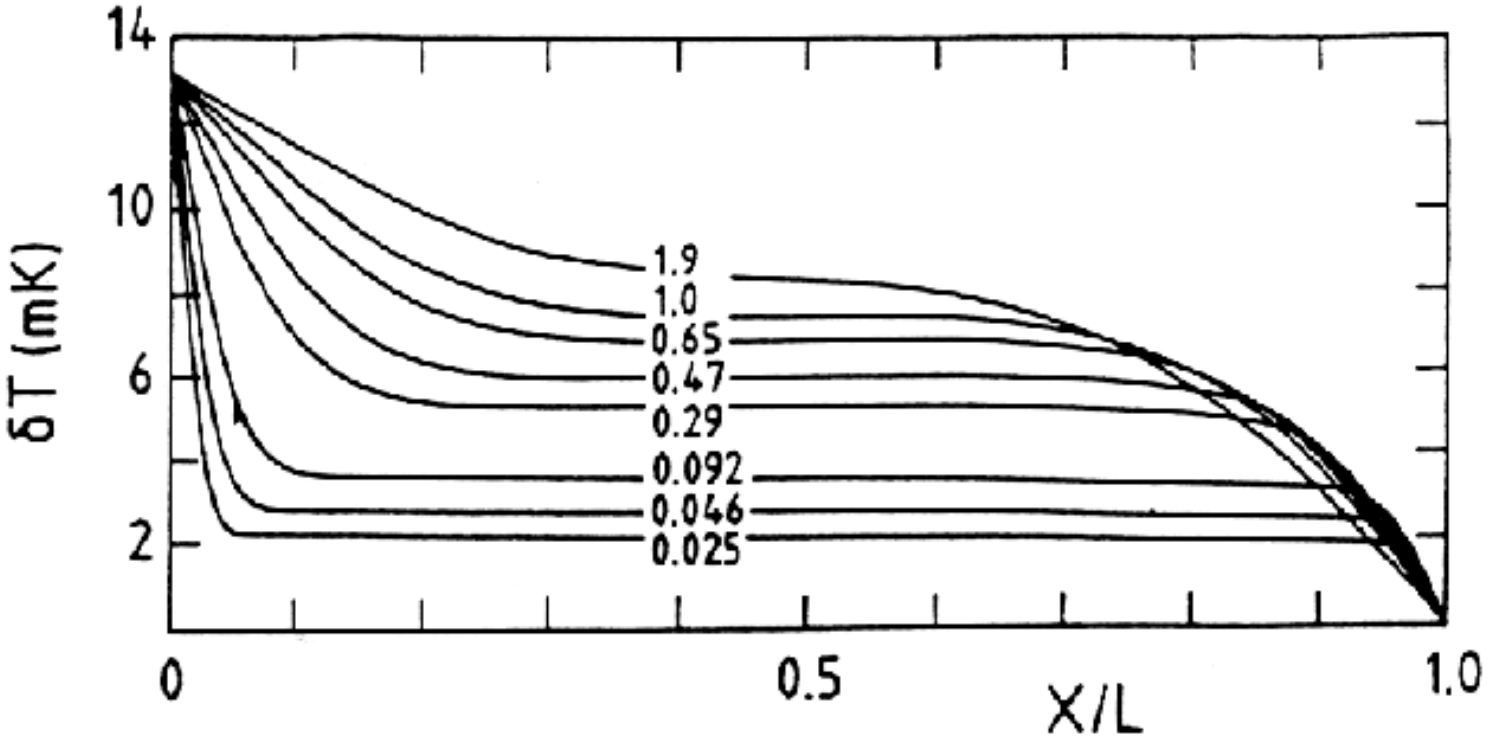
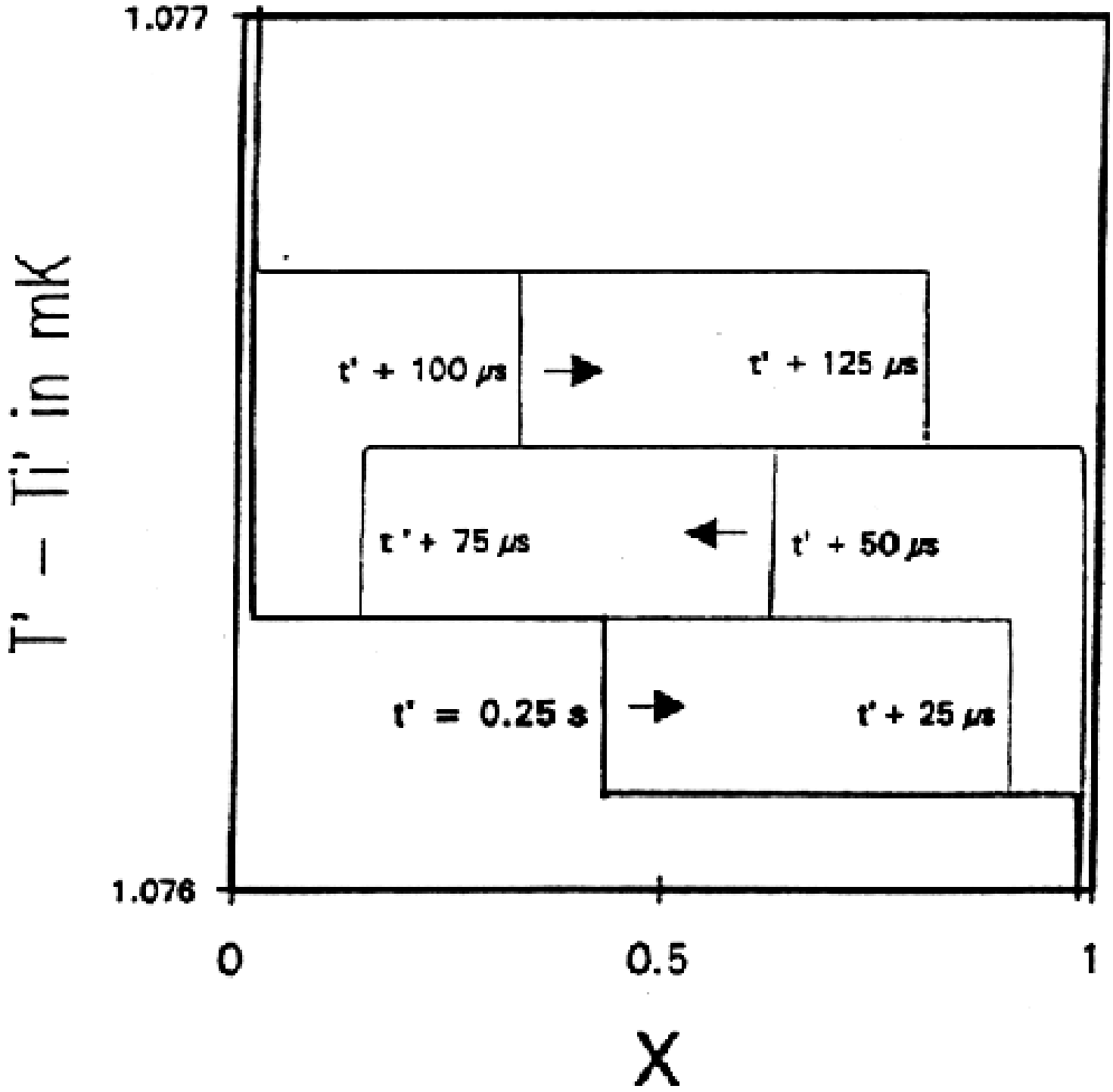


FIGURE 1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1.076
T' – Ti' in mK
t' + 100 μs
t' + 125 μs
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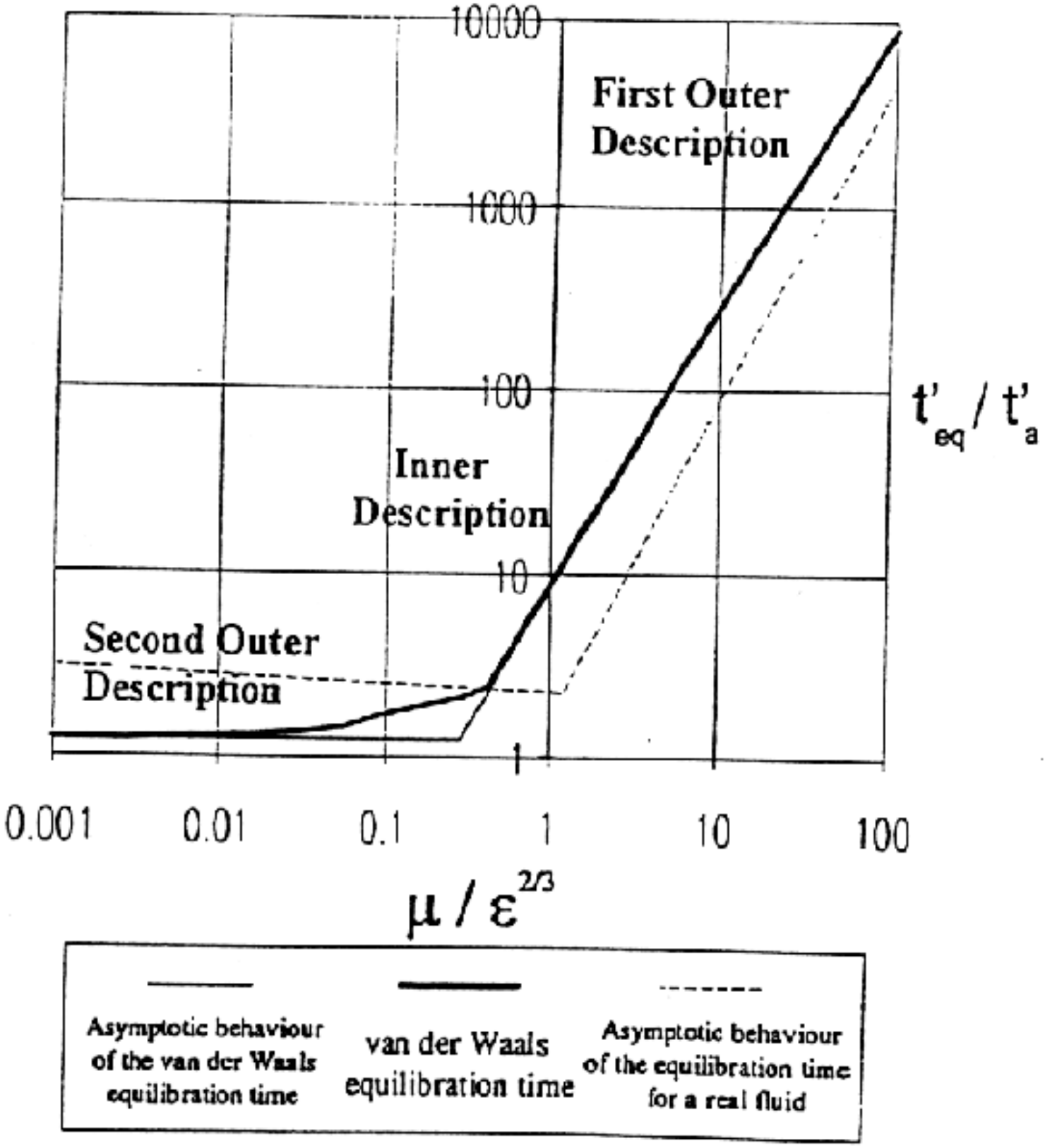
0.5
1
X

FIGURE 2


10000
1000
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First Outer Description
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t'eq / t'a
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μ / ε^2/3
Asymptotic behaviour of the van der Waals equilibration time
van der Waals equilibration time
Asymptotic behaviour of the equilibration time for a real fluid

FIGURE 3

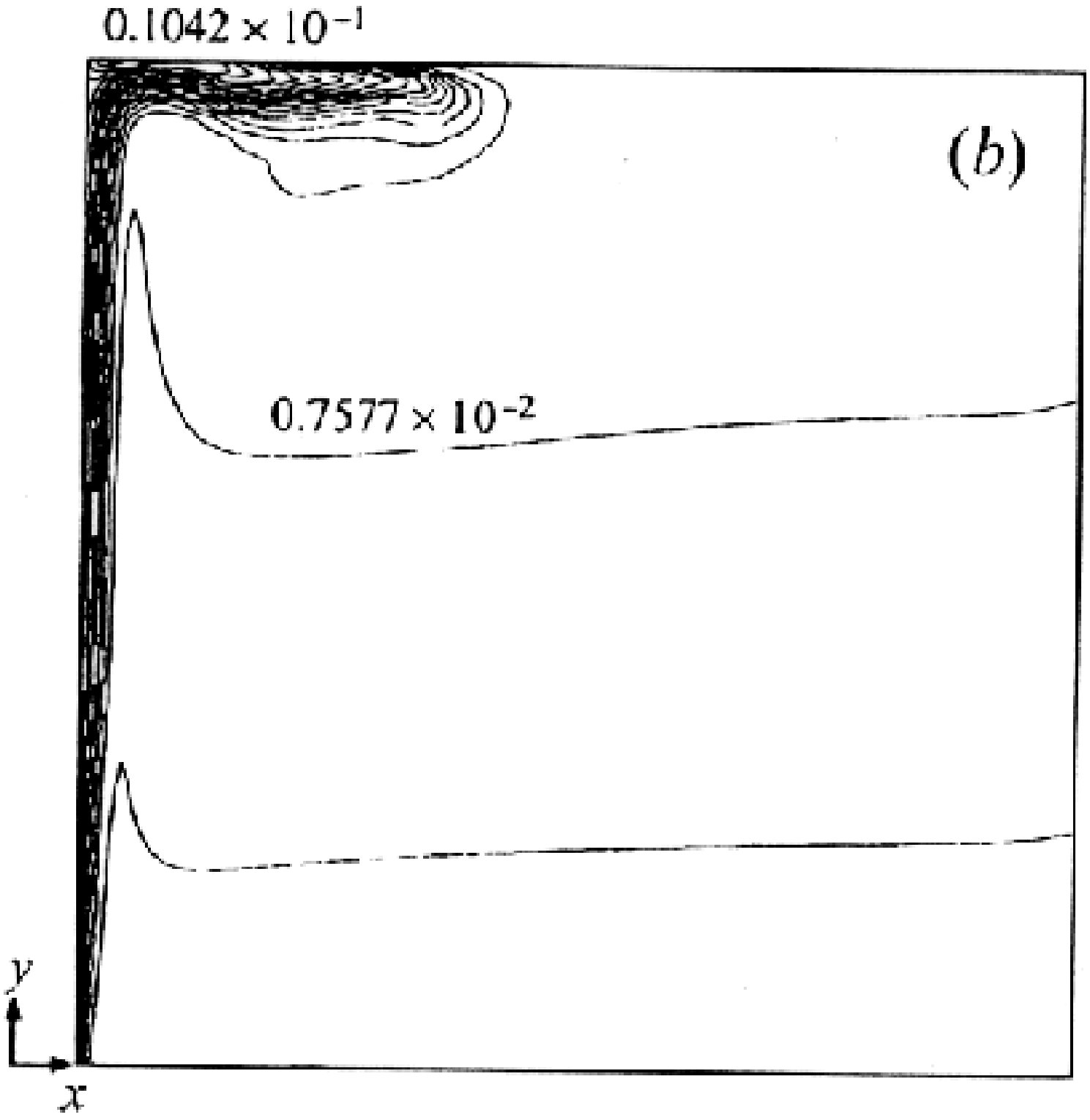


FIGURE 4

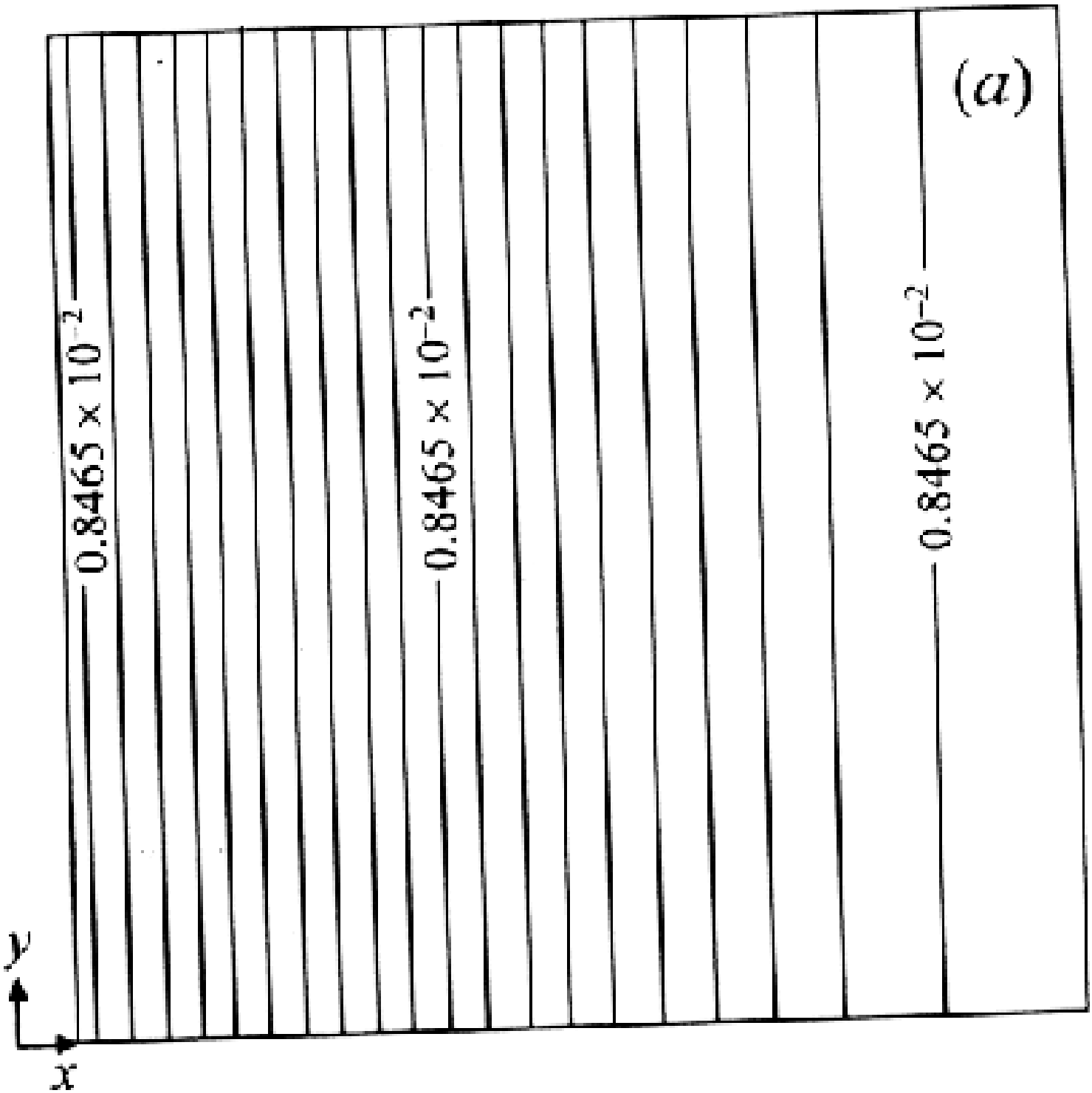


FIGURE 5

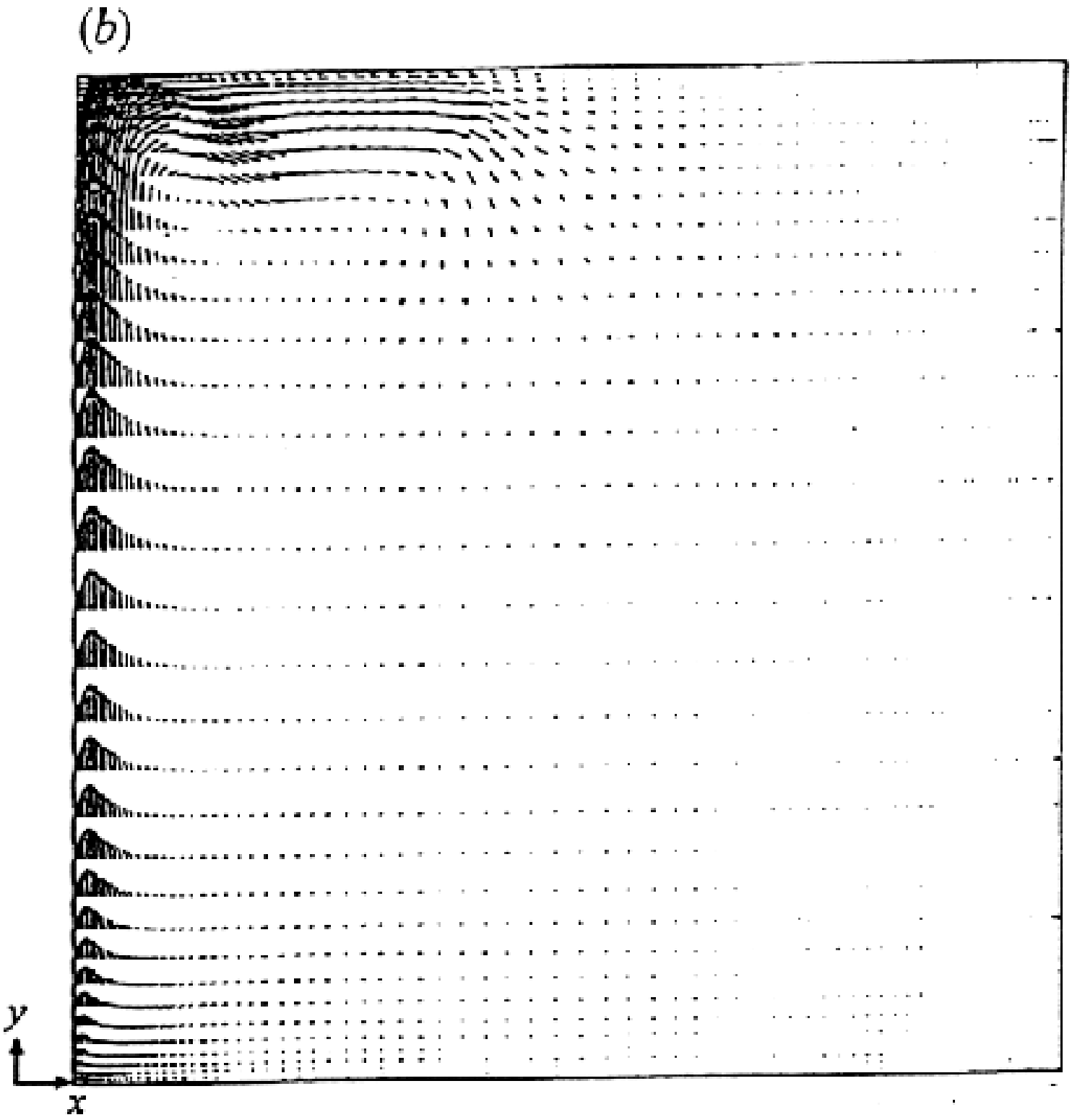


FIGURE 6

(a)

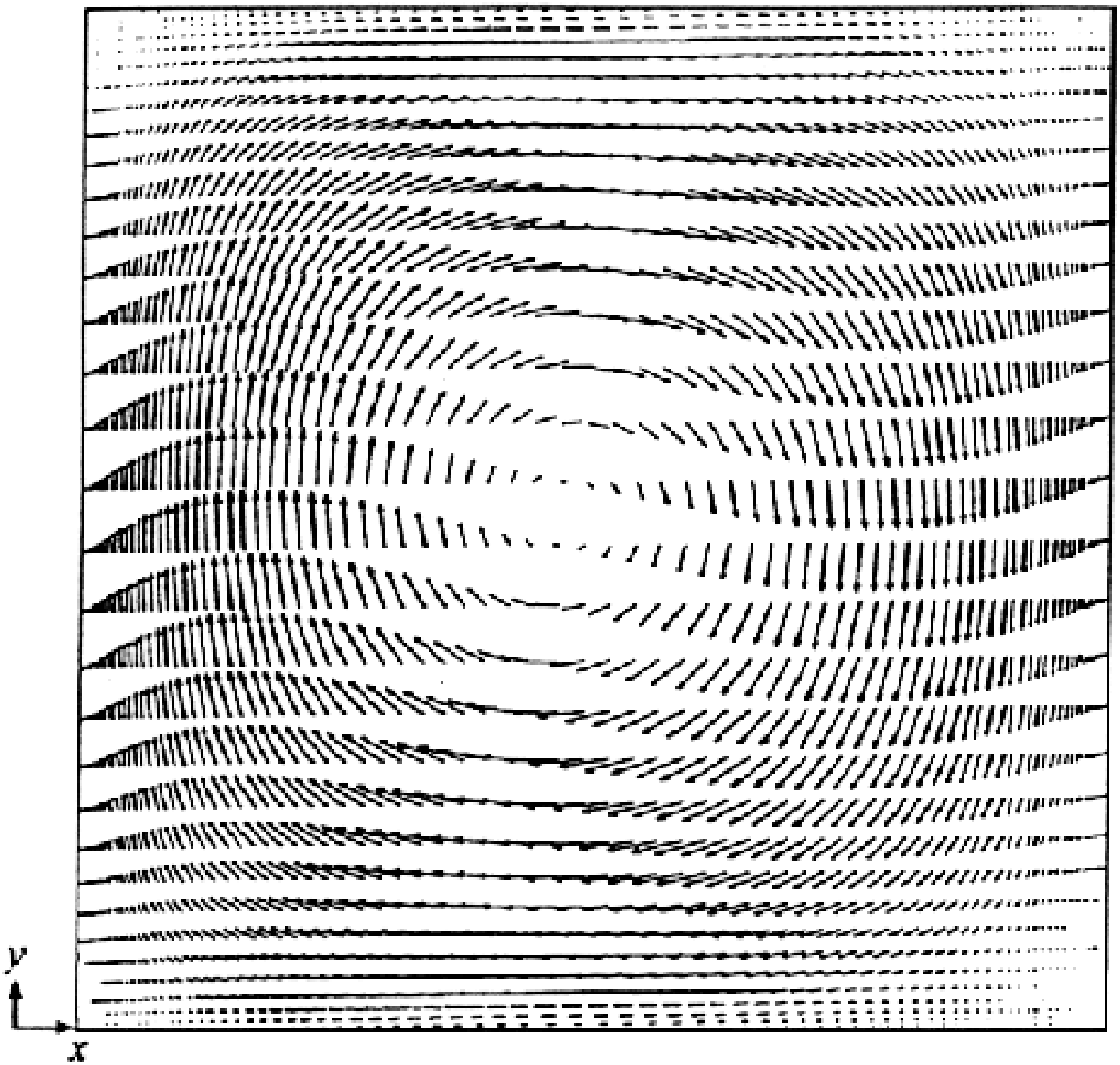


FIGURE 7

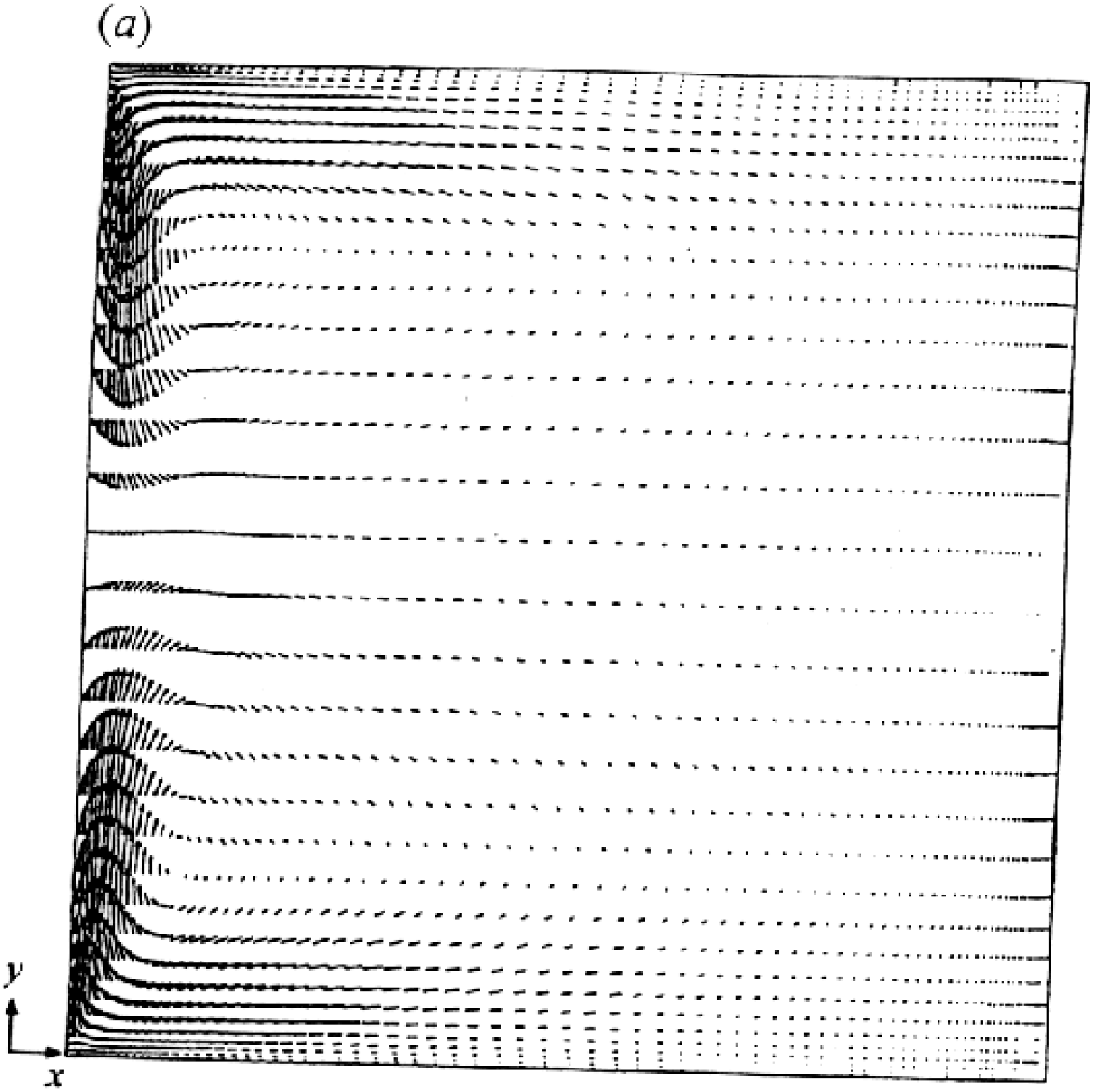


FIGURE 8

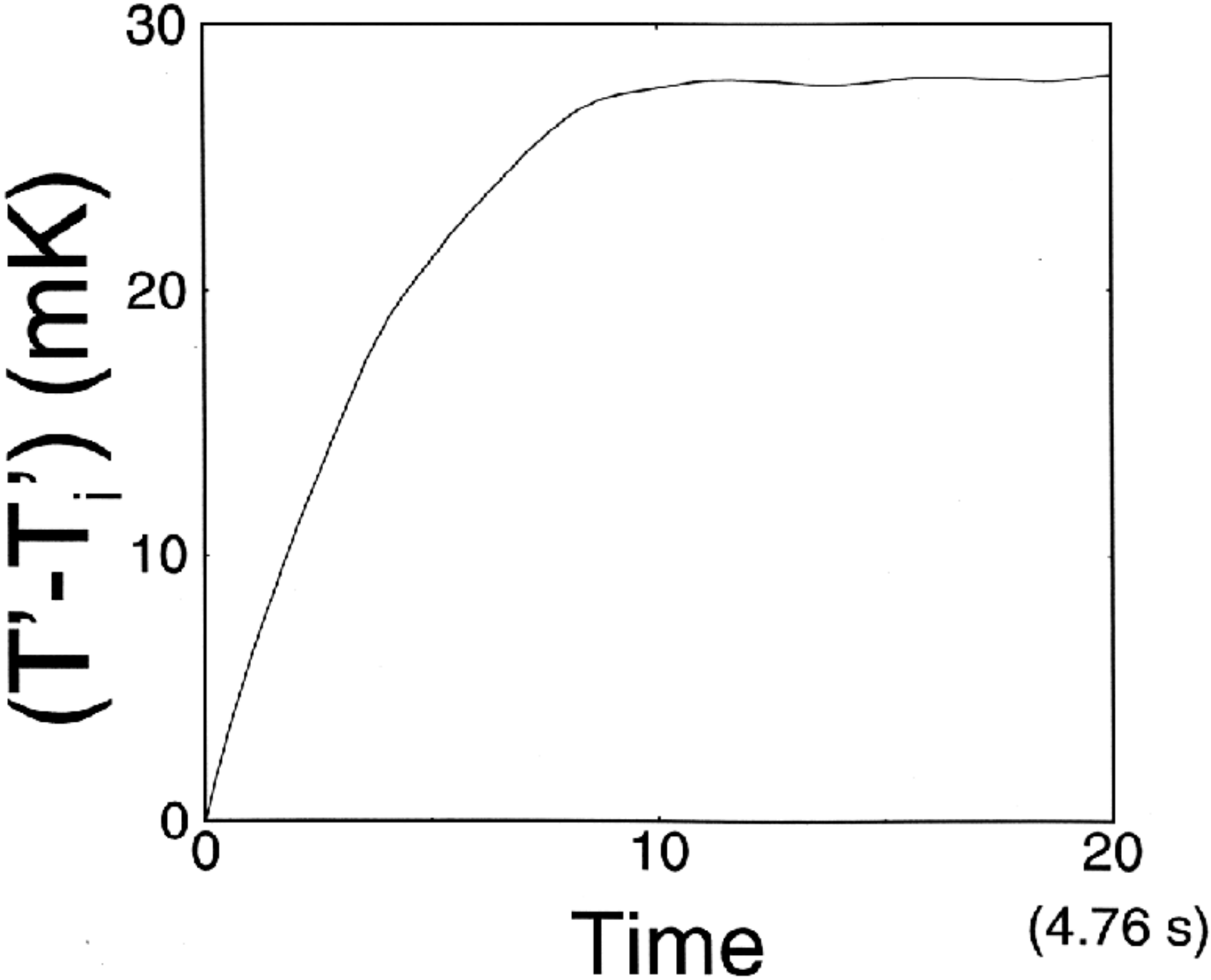
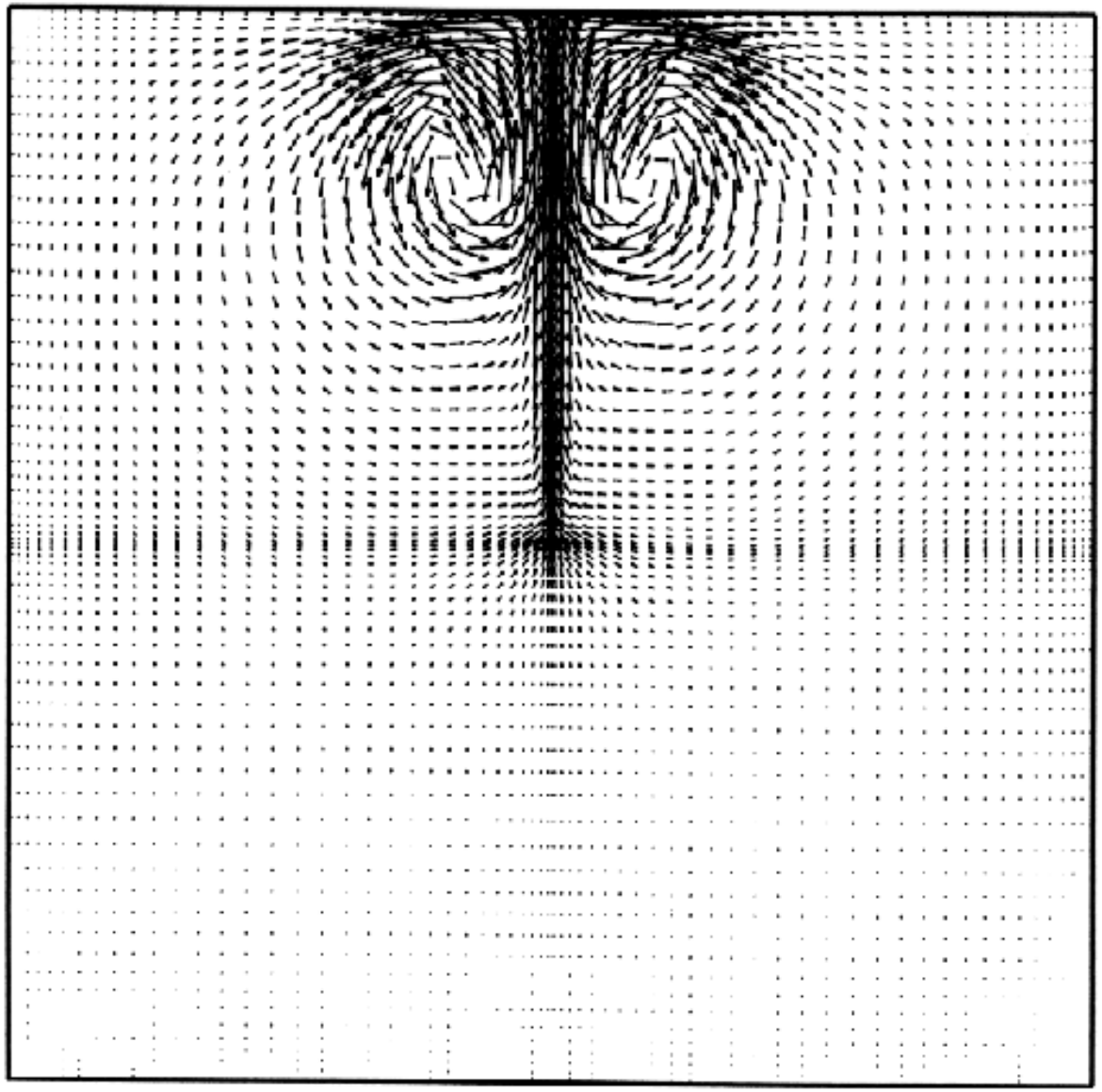


FIGURE 9



(τ=3.6)

FIGURE 10