Song and Richards argue that since the paths of the P-waves through Earth are essentially fixed, their shorter travel time between Sandwich and Alaska progressively over the 28-year period can take place only if the angle between the paths of P-wave and the fast axis of anisotropy gets gradually reduced. This reduction in the angle is possible only if the inner core rotates, a feature predicted by Glatzmaier and Roberts earlier. The inferences deduced by Song and Richards from past seismic recordings were further strengthened when they noticed that the travel time between Kermadec and Norway, stations which were initially close the fast axis of anisotropy, showed an increase with the passage of time, a clear indication that these two stations are no longer close to this fast axis (Figure 2). Their calculations indicate that the 'inner core rotates about the N–S axis like the rest of the planet, but at a rate that is 1.1° faster', eastwards.

However, subsequent work by Wei-Jia Su and his colleagues from Harvard and University of California, Berkeley, evaluating a 29-year data from International Seismological Centre (1964–1992) has revealed that the inner core rotates about 3° per year faster[12].

The differential spin of the inner core was, in fact, envisaged as early as 1986 and 1989 by the Indian scientist J. J. Rawal, Nehru Planetarium[13], Bombay, as an outcome of the progressive slowing down of the spin of the Earth, a view endorsed later by Raymond Jeanloz, University of California, Berkeley. They felt that this slowing down is due to friction caused by lunar and solar tides and that this deceleration is not fully transmitted to the inner core owing to the existence of a fluid zone of outer core separating it from the rest of the planet. According to Jeanloz, the inner core is rotating presently at a rate Earth's surface was doing some 60,000 to 100,000 years ago.

These findings about the inner core rotation can have great bearing on our understanding of the physics and chemistry of the core, particularly about the outer core viscosity, its temperature and melting conditions, heat flux across the core–mantle boundary, about the dynamo action, geomagnetic reversals and the precession of equinoxes.

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SCIENTIFIC CORRESPONDENCE

Does steam cause a more severe burn than boiling water?

May be not necessarily. This question is making rounds of our high schools and examinations and has even entered the popular science literature. Often it is posed in such a way that we are not asked to choose whether it is right or wrong but to explain why it is so. The *expected* answer, we know, is that steam causes a more severe burn due to the high latent heat of evaporation.

The question whether steam causes a more severe burn than boiling water is vague and ill-posed and strictly speaking cannot be answered. But what is being done here is to see how far can we rationalize this question and push analysis to understand the related issues. This exercise should also warn us while posing similar *clever* questions.

Steam and boiling water can exist at varying temperatures but it is only correct to assume here that both are at the same temperature. But this aspect is not as simple as it appears. We may have them at the same temperature at the source, but that does not necessarily mean that they will be at the same temperature when they contact the skin to cause a burn. This problem will be discussed later.

Water indeed has an impressively high latent heat of evaporation $H = 2.257 \times 10^6$ J/kg at 100°C and this aspect must have led some science teacher to coin this question. It is quite possible that the question has been

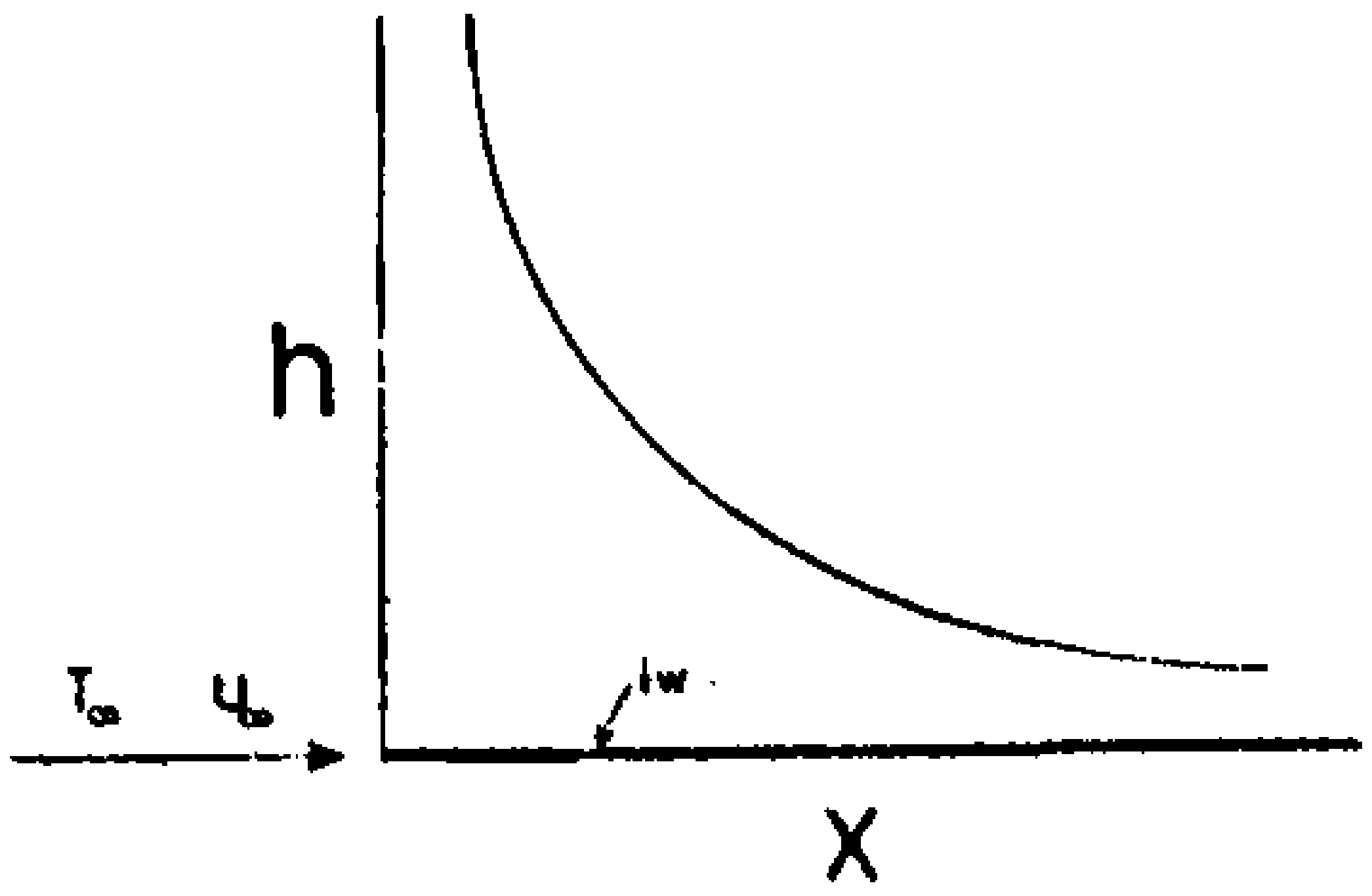

Figure 1. Heat transfer coefficient *h* due to flow along a flat plate.

Table 1. Properties of saturated water and dry steam at 100°C at one atmospheric pressure

Quantity	Water	Steam	Units
Density, ρ	960.63	0.5977	kg/m^3
Specific heat, C_p	4216.1	2076	J/kg°C
Viscosity, μ	2.8×10^{-4}	12.45×10^{-6}	kg/ms
Kinematic viscosity, ν	0.294×10^{-6}	20.83×10^{-6}	m^2/s
Thermal conductivity, k	0.68	0.02408	W/m°C
Prandtl number, Pr	1.74	1.07	–

Enthalpy of evaporation (Latent heat) $H = 2.257 \times 10^6$ J/kg.

Table 2. Non-dimensional variables appearing in this analysis

Reynolds number $Re_x = u_\infty x/\nu$
Reynolds number $Re = v_0 d/\nu$
Prandtl number $Pr = \mu C_p/k$
Nusselt number $Nu = hx/k$ or hd/k

reinvented. Luckily the expected answer has been uniformly the same. But this innocent-looking question fits into a class where only qualitative arguments are used while completely ignoring other important aspects that are involved. The experimental observation is usually ignored or selectively chosen to strengthen the proposition.

The severity of a burn depends on the high temperature to which the skin and the flesh are raised, how long this temperature is held and the area (or volume) of the affected body. The temperature of the affected area will be higher if heat is supplied at a higher rate and also if it diffuses away at a slower rate. If a hot fluid (water or steam) comes in contact with skin, several factors decide how much it affects the skin – the temperature, density, velocity, thermal conductivity, specific heat, latent heat, how much fluid is there and whether it is replenished, how long it is in contact, etc. A droplet of boiling water that falls on the skin quickly loses its heat and cannot cause much damage but a larger volume of it can cause a severe scald. Thermal properties of the skin and the surrounding tissue also play an important role.

Now a quantitative comparison is made for two simple model problems to understand *the interplay of various factors*.

Flow over a flat plate

This simple model is considered for comparison between heat transfer when either water or steam at temperature $T_\infty = 100°C$ flows with velocity u_∞ over a semi-infinite flat plate held at temperature T_w. The distance along the plate x is measured from the leading edge as shown in Figure 1. In the case of human skin $T_w = 34°C$. We assume that the flow remains laminar without becoming turbulent. Even though the steam is bound to condense on the plate, we ignore it at this stage to study the effect of other factors involved.

Heat flux q (in W/m^2) is given by

$$q = h\Delta T,$$

where h is the average heat transfer coefficient and $\Delta T = T_\infty - T_w$ is the temperature difference which may be taken to be 100–34 = 66°C. Reynolds number Re_x (see Table 2) and Prandtl number Pr affect h which is usually expressed by proper scaling in terms of the Nusselt number $Nu = hx/k$. Expressions for Nu for different problems are available in the books on convective heat transfer. From the expression for Nu for the present laminar boundary layer case we obtain

$$h = 0.664\,(k/x)\,Re_x^{1/2}\,Pr^{1/3}.$$

The value of h decreases as one moves along the flow as shown in Figure 1. The singularity at $x = 0$ is integrable and also does not cause any problem for comparison purpose. We use suffix w for water and st for steam. The heat transfer coefficients h_w due to water and h_{st} due to steam can be compared at the same location:

$$(h_w/h_{st}) = (k_w/k_{st})((Re_x)_w/(Re_x)_{st})^{1/2}\,(Pr_w/Pr_{st})^{1/3}.$$

Now k and Pr are fluid properties but Re_x is a flow property since it depends on u_∞ and x also. Then to make a comparison we have to know the values of Re_x in both the cases. We consider the two cases here – same u_∞ or same Re_x.

Case I. Comparison for same u_∞

If u_∞ is the same for the two cases of either water or steam flowing, then Re_x scales like $1/\nu$ leading to

$$(h_w/h_{st}) = (k_w/k_{st})(\nu_{st}/\nu_w)^{1/2}\,(Pr_w/Pr_{st})^{1/3}.$$

Substitution of values for fluid properties from Table 1 gives

$$(h_w/h_{st}) = (28.2)(8.4)(1.18) = 280.$$

This means that heat transfer rate is higher in case of water by a factor of 280. This factor is due to higher conductivity of water (28.2 times), higher kinematic viscosity which is due to higher density (8.4 times) and higher Prandtl number (1.18 times). Of course, we have avoided the question of latent heat for the time being.

Case II. Comparison for same Re_x

We take another case here where Re_x is assumed to be the same in both the cases. This case is selected because of its simplicity. Then

$$(h_w/h_{st}) = (k_w/k_{st})(1)^{1/2}(Pr_w/Pr_{st})^{1/3} = (28.2)\,(1)\,(1.18) = 33.2.$$

Here high k and Pr of water lead to 33.2-fold increase in heat transfer as compared to that due to steam. Note that to maintain the same Re_x, steam has to move much faster – by a factor $(\nu_{st}/\nu_w) = 70.9$. Even then water can burn the skin more severely, if we ignore the latent heat of condensation.

The case of jet impingement

Here we assume that a jet of fluid (boiling water or steam) with velocity v_0 impinges on a flat plate, modelling the skin, as shown in Figure 2. The jet has a diameter d and its exit is at a distance Z from the plate. S is the stagnation point and we compare heat transfer in the neighbourhood of this point. Suffix '0' is assigned to the values at this point. The Nusselt number at this point $Nu_0 = h_0 d/k$. Nu_0 depends on the non-dimensional parameters Re, Pr, Z/d. It also depends on other parameters like turbulence level in the jet, nozzle shape and the boundary conditions at the wall and has the form

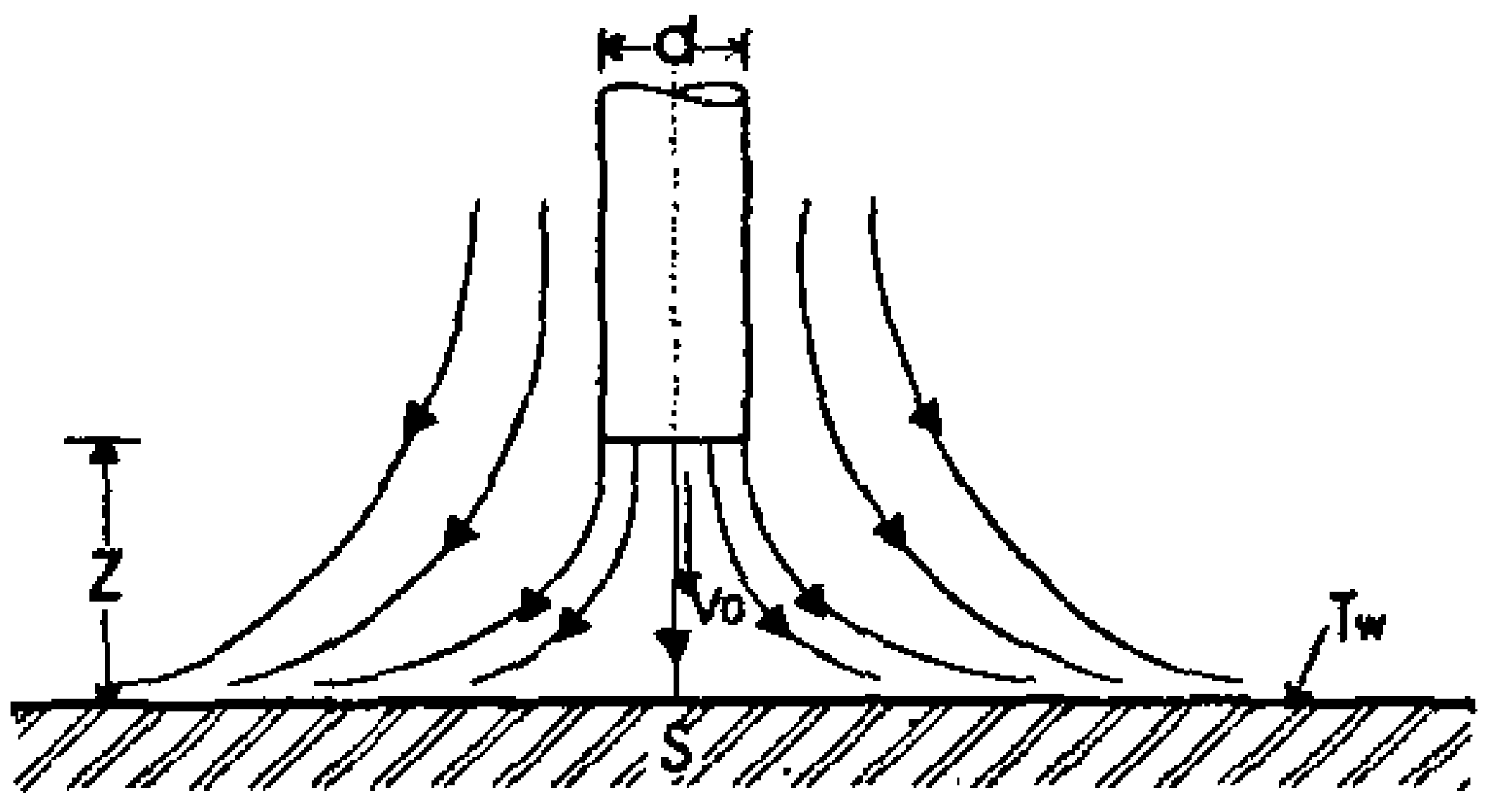

Figure 2. Jet impingement on a wall.

$$Nu_0 = CRe^n Pr^{0.4} (Z/d)^m.$$

An essential difference between the two jets should be mentioned here. The above expression pertains to a fluid jet immersed in the same fluid. Hence it can be a reasonable approximation for steam jet immersed in air or water jet immersed in water but not water jet immersed in air. There are reasons to believe that a water jet in air leads to a higher value of Nu_0 than when immersed in water and hence in what follows Nu_0 will be an underestimate if we take the same expression for water jet in air also. V. Krishnamoorthy has done extensive experiments to quantify Nu and has determined the constants C, n and m as functions of other parameters. I borrow the constants from his results but do not particularly bother to read these constants very precisely, since the final comparison and the arguments are not sensitive to them and also because of the uncertainties involved in the parameters of the problem. Taking $Z/d = 10$ and $Re \approx 10{,}000$ we get from the above mentioned experimental data $m = 0.5$, $n = 0.5$ and $C = 0.2372$. Then

$$Nu_0 = 0.75\,(Re)^{0.5}\,(Pr)^{0.4}$$

or

$$(h_0)_w/(h_0)_{st} = (k_w/k_{st})(\nu_{st}/\nu_w)^{1/2}\,(Pr_w/Pr_{st})^{0.4}.$$

Equipped with this expression, we follow the same procedure as in the case of flow over a flat plate – ignore condensation from steam and then take up two cases:

Case I. Comparison for same v_0

$$(h_0)_w/(h_0)_{st} = (28.2)\,(8.4)\,(1.215) = 288.7.$$

Case II. Comparison for same Re

$$(h_0)_w/(h_0)_{st} = (28.2)\,(1)\,(1.215) = 34.3$$

As mentioned before, steam jet velocity should be 70.9 times water jet velocity to maintain equal Re. In either case the factor 28.2 is due to high k_w, 8.4 due to low ν_w which is due to high ρ_w and 1.215 due to high Pr_w.

Steam jet impingement with condensation on wall

Let us try to estimate the effects of latent heat now and see by what factor it enhances heat transfer to the plate (skin). Condensation on the skin is a complicated process but we will make a simple assumption here that allows us to calculate this. Let

Q = Flow of heat energy in steam above skin (plate) temp. (in W)

$= (\rho v_0 A_j)\,(\Delta T) C_p$,

where $A_j = \pi d^2/4$ = jet exit area, m = mass flux $= \rho v_0 A_j$ and

q = Heat flux to the plate (in W/m^2)

$= h\Delta T$.

In the expression for Q, we have ignored the latent heat term since Q is a reference value from no condensation case. If we consider $A = \pi d^2/4$ as a reference area on the plate which is equal to the jet exit area (it is by no means critical),

$r = qA/Q$ = fraction of heat energy of jet transferred to this area.

Now the assumption is that the same fraction r of m is going to condense on this reference area A. Then the condensed mass flux $m_{cond} = rm$ (in kg/s), and the heat flux due to latent heat by steam condensation

$$q_{cond} = m_{cond}H/A = rmH/A.$$

Substituting the proper expressions and the numerical values

$$q_{cond}/q = H/(\Delta T C_p) = 16.47.$$

This ratio means that heat released due to condensation is about 16 times the heat transfer from steam if there were no condensation, other parameters being the same. This factor even though looks large is still smaller than the ratio $h_w/h_{st} = 34.3$ for even the case of same Re. For the same water and steam velocity h_w/h_{st} has a much higher ratio of 288.7.

More about condensation

We have purposely avoided till now considering details of the process of condensation itself. Even in the previous section an *ad hoc* assumption was made. Condensation depends on several factors and hence a direct comparison for the present purpose is not possible. Condensation on a surface takes place is the surface temperature is below the saturation temperature of the vapour. If the condensed liquid wets the surface, like water on skin, film condensation takes place, as against dropwise condensation. Dropwise condensation leads to a higher heat transfer rate. In either case the latent heat of condensation is imparted to the surface. The surface temperature goes up unless it is taken away by conduction or other means.

If steam at saturation temperature T_s condenses on a plate at uniform and steady temperature T_{wall}, a liquid film develops on the wall. The interface between the liquid film and steam is at temperature T_i which is only slightly lower than T_s. The rate at which condensation heat transfer takes place by film condensation on a vertical plate is given by the Nusselt formula

$$h_f = \left[\frac{g\rho_w k_w^3 H}{4\nu_w (T_i - T_{wall}) Z}\right]^{1/4}.$$

Here Z is the distance measured down from the top edge of the plate.

For the interfacial heat transfer (which should be equal to the transfer in the film to the wall in the 1-dimensional model) we have the expression

$$h_i = \frac{q}{T_s - T_i} = \frac{2\sigma}{2-\sigma}\frac{H^2\rho_{st}}{\sqrt{2\pi R T_s^3}},$$

where R is the gas constant for steam and σ is the condensation coefficient. It may be mentioned that inert gases like air mixed in the vapour greatly inhibit condensation and hence heat transfer. Since $h_i >> h_f$, the total resistance to condensation heat transfer

$$\frac{1}{h_{cond}} = \frac{1}{h_f} + \frac{1}{h_i} \approx \frac{1}{h_f}.$$

Then,

$$h_{cond} \approx \left[\frac{g\rho_w k_w^3 H}{4\nu_w (T_s - T_{wall}) Z}\right]^{1/4}.$$

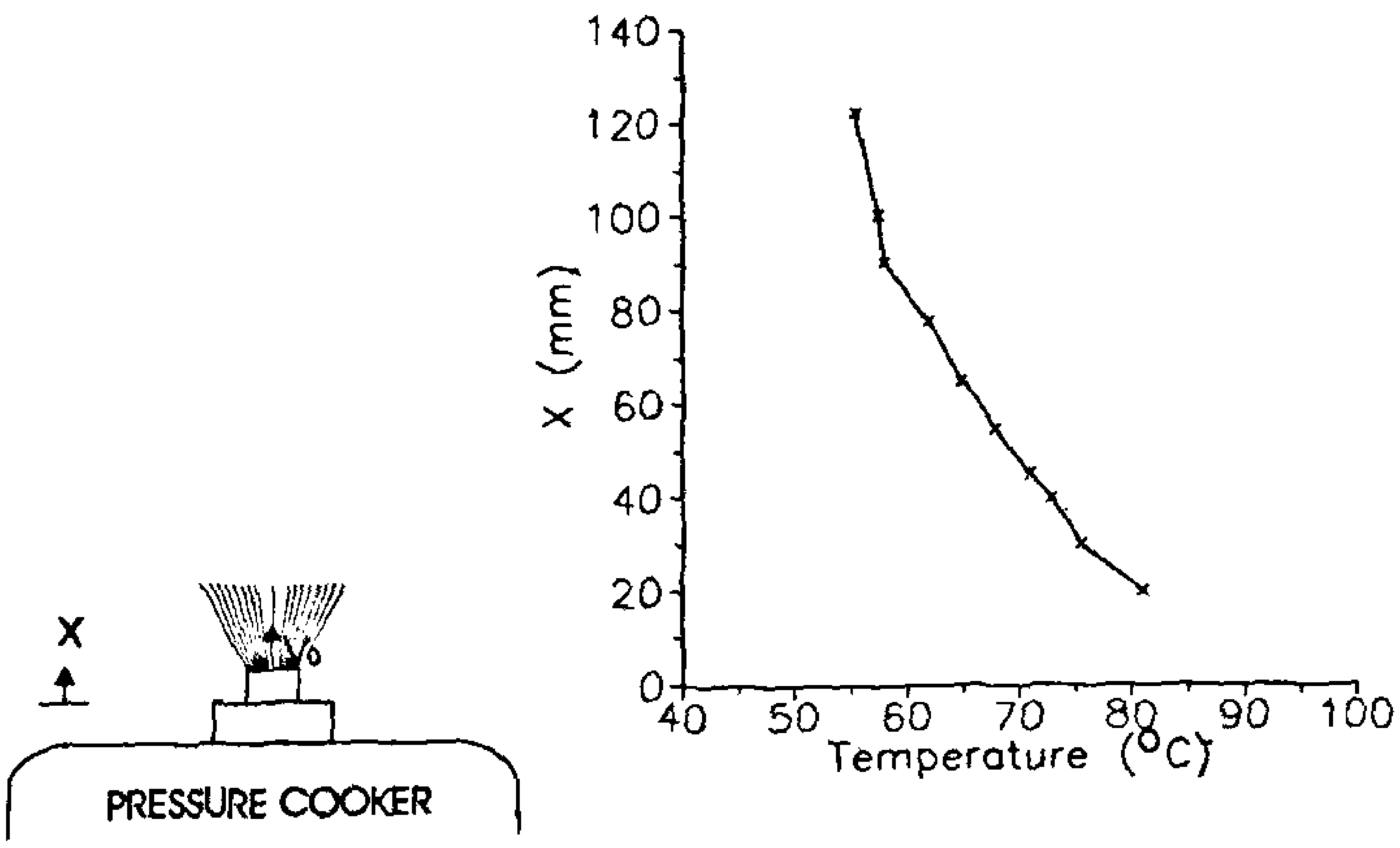

Figure 3. Temperature along the axis of a steam jet of 5 mm exit diameter.

This has a singularity at $Z = 0$ which is a modelling artefact. Getting an average value of h_{cond} by integrating up to a length L,

$$\bar{h}_{cond} = \frac{4}{3} h_{cond}(L).$$

For $Z = 0.01$ m, we get $\bar{h}_{cond} =$ 12,850 W/(m^2°C).

See that it is not easy to compare it with the boiling water case unless we have all the details in both the cases, since the actual value depends strongly on the details. For the flow over a flat plate case, for example, $\bar{h} = 2h(L)$. Substituting the values for water we get $\bar{h} = 2{,}003\sqrt{u_\infty / x}$. If we take $u_\infty = 1$ m/s and $x = 0.01$ m, we get $\bar{h} =$ 20,030 W/m^2°C. Different accident models and numerical values lead to heat transfer rates where either case may have a higher value.

The actual case when the skin is exposed to steam is an unsteady one. To start with, there is no film of condensed water and hence the skin is exposed to a very large heat transfer given by the coefficient h_i above. But it is only for a very short time and the thin film of water formed retards the heat flow. As it gets thicker its resistance increases and also since the skin is getting hotter the temperature difference causing the heat flow decreases. The formula given above for numerical estimation pertains to the steady state case. But see that when the steady state is reached, the temperature difference will be much smaller than 66°C.

What does it mean?

Since the question posed was vague, we have tried to rationalize it, as best as it can be done. Latent heat of steam is very high. (A feel for the very high latent heat of evaporation of water can be obtained by calculating the ratio $H/C_p = 535$°C. Thus only one gram of steam condensing in 535 g of water can raise its temperature by 1°C.) But there are other factors too. Water has high thermal conductivity and density (hence low kinematic viscosity). Because these aspects counteract, a quantitative analysis is required. This is done by modelling and we see that for the jet impingement problem the heat transfer from boiling water is much higher than that from steam at the same temperature, provided steam does not condense. The amount of steam that condenses has been obtained by making some assumptions. Then heat transfer from the condensing steam increases by a factor greater than 16. This factor, even though large, is still smaller than for the case of heat transfer from boiling water.

A word of caution is required here. We should not take these factors literally because of the assumptions involved. The two factors 16.47 and 34.3 are not really far apart. They indicate that it is possible to adjust parameters so that the first factor (16.47 here) can even be greater than the second one, i.e. condensing steam does cause a more severe burn. But it does not always happen.

The factors calculated in the two model problems (Laminar flow over a flat plate and turbulent jet impingement) turned out to be almost the same for similar conditions. This indicates that the present comparison is not sensitive to the mathematical model used. But it should be noted that it is true only for a comparison for similar conditions. The value of heat transfer, on the other hand, depends very strongly on the magnitudes of the parameters like fluid temperature, fluid mass involved, contact time, mass and rate of steam condensation, fluid velocity, whether the flow is laminar or turbulent, etc. The accident causing a burn is likely to be an unsteady process of a short duration, the values of the parameters being peculiar to each case. *That is why modelling this problem and drawing any general conclusions are not possible.*

On the other hand, there are some aspects on which we may comment. Steam jet usually has a higher velocity than that of a water jet. Water sticks to the body (unlike steam) thereby causing a longer contact. Steam that is issuing out in the form of a jet expands when it comes out and later the ambient air mixes with it which is called 'entrainment'. The entrainment cools the steam jet. This is shown in Figure 3 where I have plotted the temperature along the axis of a steam jet of 5 mm exit diameter. The steam jet was created from an ordinary pressure cooker by removing the weight. The bulb of the thermometer used was rather large and hence the measured values of temperature are likely to be lower than the actual values, the errors being larger closer to the exit (small X). Despite its crudeness, the experiment is adequate for the present demonstration.

Hot tea (temp ~60°C) can cause a severe burn (believe me). But how is it that we drink it and even enjoy its warmth? It is because we have mastered taking a sip that comes in the form of a sheet and gets cooled by air before coming in contact with the lips. Try drinking it with a straw; but be careful, you may burn your tongue.

It has not been verified experimentally or otherwise that steam causes a more severe burn than boiling water. But such notions persist because we get conditioned at a weaker moment, say when we study a chapter on latent heat. To remove such an ill-founded question, even though there is no supporting evidence, from mass circulation is not easy. It is because of the difficulties involved in getting a convincing quantitative answer when several factors are involved.

The problem we are discussing may sound innocent, specially because the *expected* answer sounds convincing, is simple to give and is uniformly accepted. A more serious problem is faced by undergraduate students while conducting experiments involving physical systems. Often there are many parameters that contaminate the experiment. The students do not have a good understanding of these extraneous factors, leave aside a good control over them in the experiment. These become a more serious handicap than the inaccuracies in the instruments. But the students are obliged to get an 'expected' answer and often 'cook up' the results. Experiments in the chemistry curriculum, in my experience, are usually better controlled and one becomes confident after successfully getting the answers.

Coming back to the question on burns, it is not always simple to decide which of the two burns is more severe. And regarding the problem we are discussing, I checked with a couple of doctors what they have in the medical literature. They do not bother whether the burn is caused by steam or water. They go by a different classification of the burns. Probably they are forced to be more honest since there is a serious problem in hand.

It may be interesting to mention here about the damage due to cold where the heat is extracted from the body. Air at 1°C makes us uncomfortable but we can survive it. But a human being in water at 1°C cannot survive it for more than 30 minutes. This is because of higher density, thermal conductivity and specific heat of water as compared to those of air. The question of latent heat does not arise here.

Does steam cause a more severe burn than boiling water? It may; it may not also. The question is not proper. I do not give an answer, but I have an explanation.

ACKNOWLEDGEMENTS. I thank my colleagues Dr P. N. Shankar and Dr V. Krishnamoorthy and an anonymous referee for making helpful suggestions and Mr V. S. Narasimhan for the help rendered in preparing the figures.

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Remote sensing application for delineating coastal vegetation – A case study

Satellite remote sensing has progressed rapidly and has provided a wealth of information on land as well as near-shore regions due to its repetitive and synoptic coverage. Remote sensing data have been used extensively worldwide for mapping coastal vegetation[1–3]. Similar work, however, along the Goa coast, is reported to a lesser extent[4,5].

This study envisages the use of digital image processing techniques for delineating geomorphic features and associated vegetation, including mangrove, along the central part of the Goa coast which includes the Mandovi–Zuari estuarine complex (Figure 1).

The typical geomorphological features, supported by favourable water currents and salinity, decide the lateral growth of coastal vegetation. Hence, identifying suitable geomorphic sites along the coast and the estuaries is a major task in depicting and delineating the vegetational features.

Multi-spectral scanner (band 4,5,6,7) data pertaining to scene (Path 49, Row 142) dated 31 March 1986 of Landsat 5 were used. Sub-image (Figure 2) with 900 lines and 900 pixels, covering Mandovi and Zuari estuarine complex, was separated and digital processing was carried out using DIPIX image processing system.

Because the influence of the coastal features on each band is highly correlated, compressing all bands into a single plane improves the identification of individual features. For this purpose,

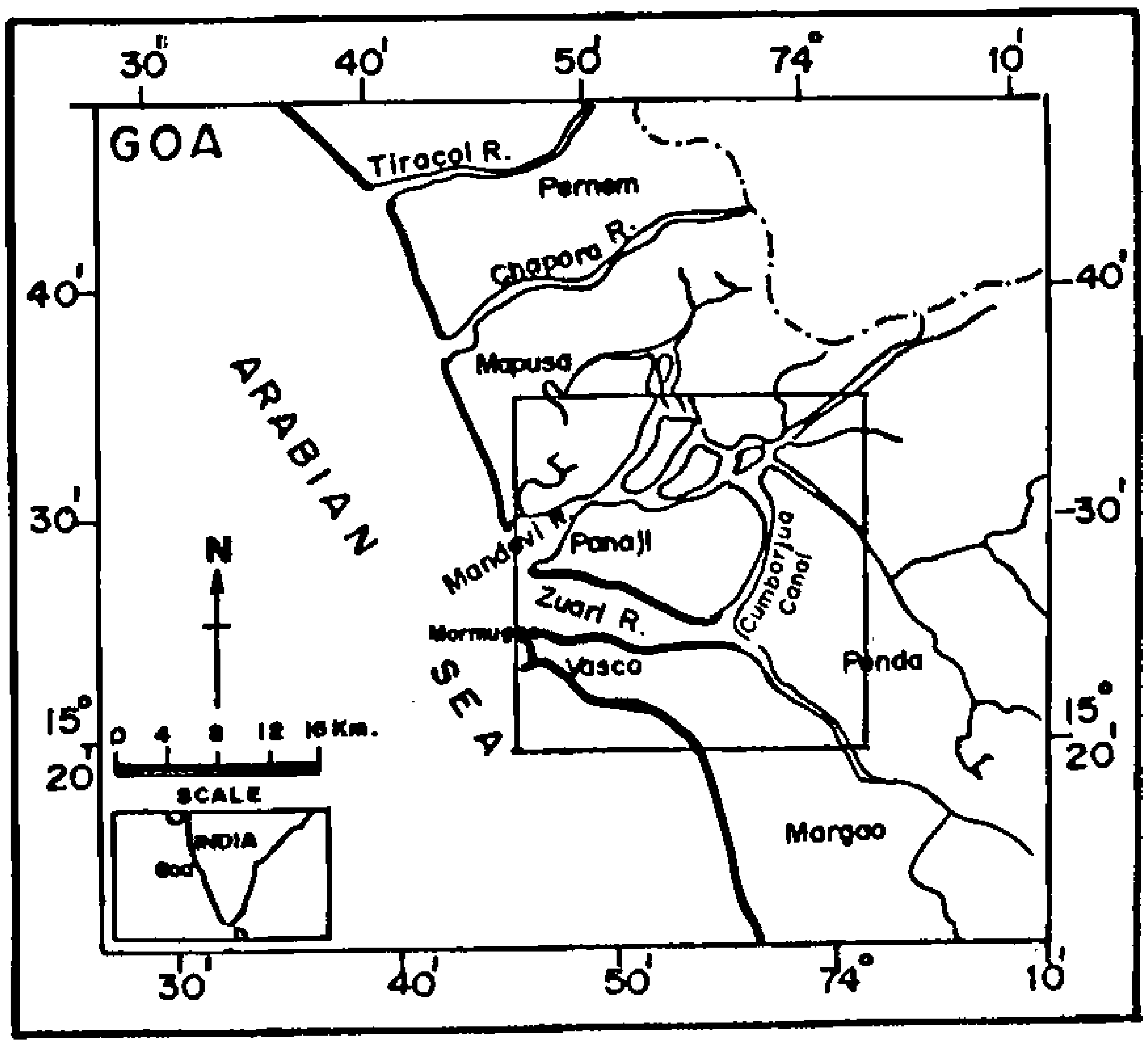

Figure 1. Location map of the study area.