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AN EXPERIMENTAL INVESTIGATION OF REAERATION IN OPEN-CHANNEL FLOW

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AN EXPERIMENTAL INVESTIGATION OF REAERATION IN OPEN-CHANNEL FLOW

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SUMMARY

Dimensional analysis of the factors affecting the reaeration coefficient k_2 for open-channel flows indicated that the reaeration variable k_2H/U should depend upon the dimensionless friction velocity U_*/U, the Reynolds number, the Schmidt number and the width to depth ratio of the flow. An experimental investigation was carried out to study this dependence. The Schmidt number was kept constant and was left out of the experimental investigation by converting the k_2 values to a common base temperature. Inspection of previous published data had shown that the width to depth ratio had little effect. The experiments were therefore designed to elucidate the dependence of k_2H/U on U_*/U and Reynolds number.

Deaerated water was introduced into a recirculating flume system and then circulated at the designed hydraulic conditions. The increase in the DO concentrations at two stations 100 feet apart were measured at intervals of time, from which the value k_2 could be calculated. Errors in measurements of k_2 had been minimized by using the 100 feet long test section and by taking extra precautions in sampling and DO analysis.

The experimental results showed that it is impossible to use one single equation to describe the reaeration rate in all systems. For large relative roughness or large Reynolds numbers, the reaeration variable depends primarily on U_*/U but for smaller values of Reynolds number and relatively smooth flow, Reynolds number has greater effect on k_2H/U than the roughness.

AN EXPERIMENTAL INVESTIGATION OF REAERATION IN OPEN-CHANNEL FLOW

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Introduction

The dissolved oxygen concentration (DO) is one of the most important indicators of the water quality of a river. While many processes affect the dissolved oxygen balance in a river and the evaluation of the DO depends on the rates at which all these processes occur, many of these processes are biological and chemical in nature and cannot be easily modelled. However, the process of oxygen absorption from the atmosphere is a physical process and can be related almost entirely to the flow conditions in the river. This atmospheric reaeration rate is the measure of the self-purification capacity of a stream and is an essential piece of information for water quality modelling.

Many theoretical models of the process of oxygen absorption into open-channel flow had been proposed. However, it has been shown (1,2) that none of these theories is suitable for the prediction of stream reaeration rates because they all involve parameters such as surface film thickness or renewal rates which have not been related to bulk hydraulic parameters. Many empirical equations, based mainly on regression analysis of experimental data, had also been put forward. Unfortunately, these equations all differ from one another in the values of the calculated reaeration coefficient K_2 and, more importantly, in the form of the dependence of K_2 on the various hydraulic variables. Lau (3) has shown that much of the discrepancy between many of the prediction equations stemmed from the experimental data not being analysed properly. In all cases, the functional dependence of the various dimensionless parameters involved had not been investigated. An attempt was made to investigate this functional dependence based on the more reliable sets of published data and a prediction equation was proposed (3,4). This equation indicated that the dimensionless reaeration parameter K_2H/u was a function of U_*/U where H and U were the mean depth and mean velocity respectively and U_* was the shear velocity. However, because of the large scatter in the data and the fact that the data were not amenable for dimensional analysis because none of the experiments were designed to vary only one independent parameter at a time, it was believed that some controlled experiments based on the results of dimensional analysis, should be performed to elucidate the dependence of the reaeration parameter on the independent parameters. This article is a report of such an experimental investigation.

Dimensional Analysis

It is well recognized that the main resistance to oxygen absorption into flowing water is in a small region close to the surface. Although the concept of a stagnant surface film is not valid, it has been shown that even with turbulence at the surface, the diffusion coefficient through the thin surface layer is still of the same order of magnitude as the molecular diffusion coefficient (5). The dissolved oxygen can be mixed within the bulk of the flow very much quicker than the diffusion rate through the surface layer. Therefore, the factor which determines the reaeration rate is the extent to which the turbulent fluctuations near the surface can penetrate the surface layer and entrain liquid rich in oxygen into the liquid below. These concepts were incorporated into some of the theoretical models such as the surface renewal theory of Danckwerts (6), the film penetration theory of Dobbins (7) and the stochastic model of Rudis and Machek (8). However, because there is as yet no theory which allows one to calculate the turbulence characteristics in any open-channel flow, the above mentioned models do not bring us any closer to a prediction equation of the reaeration rate. Under these circumstances, the best means of arriving at a reliable prediction equation would be a systematic experimental investigation based on a dimensional analysis of the problem.

The dependent parameter under investigation is the reaeration coefficient K_2 defined such that the amount of oxygen absorbed per unit volume of liquid per unit time is equal to K_2 time the oxygen deficit, i.e.,

$$\frac{dC}{dt} = K_2(C_s - C) \qquad (1)$$

where C is the dissolved oxygen concentration
C_s is the saturation concentration
and t is the time.

The reaeration coefficient depends upon molecular diffusion at the surface, characterised by D_m, the molecular diffusion coefficient, and also upon the turbulence characteristics of the flow. For a particular open channel, the flow characteristics are determined if the velocity U, the hydraulic radius R, the width of the channel W, and the density ρ and the viscosity μ of the fluid are given. Considering channels of different roughnesses, one should include either the height of the bottom roughness or the bottom shear stress or shear velocity U_*. Therefore, one can write

$$K_2 = f_1(\rho, \mu, U, R, D_m, U_*, W) \qquad (2)$$

In terms of dimensionless variables, equation (2) can be written as

$$\frac{K_2 R}{U} = f\left(\frac{UR\rho}{\mu}, \frac{U_*}{U}, \frac{\rho}{\mu D_m}, \frac{W}{R}\right) \qquad (3)$$

A number of factors have not been considered in this dimensional analysis. The Froude number, or gravity effect, was left out because its effect on open-channel flows is quite small for Froude numbers less than 0.5 or so and most natural streams fall into the low Froude number category. The possible effects of cross sectional shapes are not considered. Wind action can increase the effective surface area for absorption and thus the reaeration rate (9), but for long term averages it is a transient effect and has not been included in this study.

The dimensional analysis indicates that the dimensionless reaeration parameter K_2R/U is a function of the Reynolds number, the Schmidt number, the width to depth ratio and the ratio of shear velocity to mean velocity which in fact represents the friction factor of the flow. In order to properly investigate the relationships between the dimensionless variables, experiments should be performed by varying one of the independent variables while keeping the other three constant. The changes in K_2R/U so obtained would be the effect of that one independent variable on the dependent variable K_2R/U. With the five variables involved in equation (3), the experimental procedures can be rather complicated. However, it can be observed that the Schmidt number $\mu/(\rho D_m)$ consists of fluid properties only and is constant if the temperature is constant, since only oxygen absorption into water is under consideration here. The effect of temperature on reaeration has been studied on a number of occasions (10, 11) and the reaeration coefficient K_2 was found to increase with temperature. This increase is obviously the effect of the Schmidt number. Therefore, the Schmidt number can be left out of the experimental investigation providing the experiments are always performed at the same temperature or if the results are converted to a common base temperature. The equation generally used to correct for temperature effects is that suggested by Elmore and West (10)

$$(K_2)_{T^\circ} = (K_2)_{20^\circ}\, 1.0241^{(T-20)} \qquad (4)$$

where T is in $^\circ$C.

Some of the published data from experiments of reaeration had been analysed by Lau (3) based on equation (3). The data included those of Krenkel (12) and Thackston and Krenkel (13) which were the only published flume data with sufficient information for calculating the shear velocity. The field data of Churchill et al (14) were also used because they were considered the most reliable of all field data which were usually subject to interferences from BOD, plant respiration and other sources and sinks of DO. Even though the independent variables were not kept constant in those experiments, making the analysis somewhat difficult, it was observed that the width to depth ratio did not have much effect on the reaeration variable and neither did the Reynolds number. The reaeration variable was found to depend on the value of U_*/U and based on the three sets of data, the equation

$$\frac{k_2 H}{U} = 0.0126\left(\frac{U_*}{U}\right)^3 \qquad (5)$$

was proposed. Note that k_2 is the term generally used in the literature and is equal to $K_2/2.30$ and H, the mean depth, is used instead of R because it made little difference to the equation.

Experimental Investigation

It should be recognised that equation (5) is an equation which best fits previously available data but does not predict the data obtained in this study. Figure 1 shows the data points and the prediction equations proposed by Lau (3) and Thackston and Krenkel (13). It is at once evident that all three sets of data contain very large scatter. This high degree of scatter may be expected from the field data but certainly not from flume experiments which were performed under controlled conditions in the laboratory. Indeed, some of the data points which had the same Reynolds number and friction factor had variations in K_2H/U as high as 100%. The accuracy of these data must be considered rather suspect.

Although corrosive action in the channel or in the return pipes had been suggested by Bennett and Rathbun (2) as one possible source of error, it is the author's opinion that the main reason for the inaccuracy of the flume data was the fact that the flumes were not long enough to allow for sufficient DO change between the upstream and downstream sampling stations. For the calculation of K_2 in a recirculating flume experiment, DO measurements are made with time for both upstream and downstream stations. The logarithm of the DO deficits are then plotted against time and two parallel straight lines are then fitted to the upstream and downstream measurements respectively, as shown in Figure 2. The value of K_2 is then equal to the slope of the line joining a point A on the upstream line to a point B on the downstream line at a time lag equal to the travel time between the two stations. If the flume is short and the travel time is small, the upstream and downstream lines are actually very close together. Both the flumes used by Krenkel (12) and Thackston and Krenkel (13) were 60 feet in length and the sampling stations were about 40 feet apart. Under these circumstances the difference in DO concentration between the upstream and downstream points at any time (points A and C in Figure 2) may range from about 0.1 mg/litre to 0.05 mg/litre, which can be smaller than the DO measurement error. It is obvious that a high degree of uncertainty must accompany the fitting of the lines through the data points. As an example, if the upstream measurements were in error by 0.05 mg/litre, the value of K_2 obtained could be in error by 40 percent. In consequence it was decided that the experimental channel for this study must have as long a test section as possible in order to minimize the effect of DO measurement error. Extra precautions were also taken with regards to the sampling and measurement procedures.

Equation (5) indicates that K_2R/U varies solely with U_*/U and was affected by neither the width to depth ratio nor the Reynolds number. It is known that the width to depth ratio of an open-channel flow governs the secondary circulation and affects the diffusion rate within the flow. However the main resistance to reaeration is in the small region close to the surface and is unlikely to be affected by the secondary circulation within the flow. Thus it can be expected that the width to depth ratio would have no bearing on the reaeration variable. It is also known that in fully rough turbulent flow the flow characteristics are independent of the Reynolds number, but, at smaller values of relative roughness flow resistance and other flow characteristics do depend on the Reynolds number. Holley (4) has shown that in both heat and mass transfer, the sublayer thickness varies with the Reynolds number as well as the friction factor. Therefore it is likely that the Reynolds number would have the same effect on reaeration for certain ranges of Reynolds number and U_*/U, and it was decided to conduct a systematic investigation of these two variables on K_2R/U. The Schmidt number was essentially held constant by bringing all the results to a common temperature of $20^\circ C$ using equation (4).

Experimental Equipment

The experiments were performed in a recirculating flume consisting of an open channel, a tailbox, a recirculating pump and the return flow piping. The channel is rectangular in section, 60 centimeters wide, 15 centimeters high and 30.5 meters in length. Water flows down the flume, into the tailbox and is drawn through the variable speed axial flow turbine pump into the return piping which runs underneath the flume and then onto the upstream end of the flume. The flume is pivoted about the downstream end and can be raised or lowered with a pair of screw jacks which act as supports at approximately a third of the distance from the upstream end. To eliminate any possible corrosive action, the flume and tailbox were made of wood and painted with an epoxy paint and all the return piping was made from plastic material.

Several bed roughnesses were used. The smooth wooden bottom was used for one series of tests. Three other series of tests were made using sands of 1 millimeter and 3 millimeter mean diameters and gravel of 6.7 millimeter mean diameter as bed material. For each series of rough bed experiments, the bottom of the flume was first lined with wallpaper. A layer of varnish was then painted on the wallpaper and the roughness material was sprinkled on liberally. After drying overnight, the excess material was vacuumed off. This process resulted in beds of very uniform roughnesses.

Dissolved Oxygen Analysis

Edington et al. (15) did an extensive study of the Winkler method for dissolved oxygen measurement and conducted laboratory research to evaluate different end point detection methods, handling parameters, reagent characteristics and interfering ions etc. Because of the importance of having accurate DO measurements, a number of extra precautions were taken based on the results of their research.

The 300 ml. BOD bottles used for the samples were calibrated individually to obtain the exact volume of each bottle. The procedure involved drying, weighing, filling with deionized water and reweighing. The volume of the bottle was calculated from the weight and temperature of the water contained. Edington et al. (15) discovered that individual volumes ranged as high as 303.7 ml. In the present case the deviations were even larger. The bottles calibrated ranged in volume from 305 ml. to 296.4 ml. It was important to know the exact volume in order to make corrections in calculating the DO.

The amperometric method of end point detection was employed, using a platinum-calamel electrode pair and a microammeter. The visual method of end point detection can be in error by as much as 0.05 ppm; in a direct titration, the end point comes too soon and in a back titration the end point occurs late (15).

Most of the procedures recommended by Edington et al (15) were adopted. It is believed that the DO measurements made were more accurate than those of the previous reaeration experiments.

To provide a check for the DO measurements obtained from Winkler titrations, dissolved oxygen readings were also taken at the same time using two International Biophysics Corporation DO analysers. One dissolved oxygen electrode was placed at each sampling station and readings were taken as the water was being sampled. The electrode readings were not as reliable as the titrations because the probe calibrations can drift even in the course of one or two hours. However, most of the results compared quite well and the probes were always used except in a few tests when the flow velocities were very slow in which case use of the probes were not recommended.

Experimental Procedure

Experiments were designed so that only one independent variable was changed at a time. For a particular depth of flow experiments were ran at a number of different discharges. This meant that the Reynolds number was varied while U_*/U remained constant. The flow depth was then changed and experiments at those discharges were repeated. By running the experiments as different depths and with different bottom roughnesses but repeating the same discharges each time, the effects of U_*/U and of Reynolds number could be isolated.

Water was deoxygenated by the addition of sodium sulphite with cobalt chloride as catalyst in a large tank sitting next to the tailbox. An excess of sodium sulphite was always added. The water was allowed to sit overnight and was mixed thoroughly the next morning before being pumped into the tailbox and the flume. The flume was set in the level position and the whole system was filled to the required depth in the flume. The pump was started and adjusted to the required discharge and the slope was varied until uniform flow conditions were obtained. The system was kept running at those settings to oxidize any remaining sulphite and to allow the water in the flume to become well mixed so as to eliminate any abrupt concentration variations. There was usally 30 minutes or more of running time before the DO level would start to increase.

Samples were taken at two stations 100 feet apart. The samples were collected using specially fabricated large plastic syringes. The BOD bottles were purged with nitrogen gas and placed in a container which was flushed continuously with nitrogen to keep out any extraneous oxygen. The sample was thus dispensed into the BOD bottle under a nitrogen atmosphere. About 200 ml. of sample water was allowed to overflow before stoppering. Eight samples were usually taken at each station during any one run. Time interval between samplings varied from one run to another, depending on the reaeration rate for that particular run. After sampling was completed, some water was withdrawn from the flume, stirred until saturated and a saturation sample was taken to obtain the saturation concentration.

Results and Discussion

To investigate the effect of Reynolds number on the reaeration variable, plots of K_2H/U versus Reynolds number were made for various constant values of U_*/U. These plots are shown in Figure 3. The depth H was used instead of the hydraulics radius R out of convenience and because no difference was made whether R or H was used. Reynolds number values ranged from about 2×10^4 to 10^5. The values of k_2H/U remained constant as the Reynolds number was varied with constant U_*/U. Thus it appears that, in this range of Reynolds number at least, the reaeration variable is independent of Reynolds number. The values of k_2H/U do seem to decrease with decrease in U_*/U until U_*/U falls below about 0.08 when all the points seem to congregate about a constant value of k_2H/U.

To find out the form of the dependence on U_*/U, the data points were plotted in terms of k_2H/U versus U_*/U, as shown in Figure 4. As expected from what was shown in Figure 3, the points lay almost on one curve, with no Reynolds number effect discernable. The value of k_2H/U seems to remain constant at about 2×10^{-5} until U_*/U increases beyond 0.08 when k_2H/U increases more or less linearly with U_*/U. The lowest value of U_*/U obtained was about 0.04 for the case of smooth bed with 5 centimeter flow depth and the largest value was 0.146 for the case of gravel bed with 2 centimeters flow depth. The data points, compared with those in Figure 1, exhibit very little scatter (note the different scales of the two Figures) indicating that by using the 100 feet long test section and taking extra precautions in the DO analysis, DO measurement errors had effectively been minimized. Equation (3), which was fitted to the data of Figure 1, was also plotted in Figure 4. It can be seen that this equation does not agree very well with the present data. Because of all the reasons given previously, it is thought that the present data are more accurate.

Although the data showed, as expected, that the reaeration variable depended only on U_*/U at high values of U_*/U, i.e. large relative roughnesses, the constant value for k_2H/U at the smaller values of $U*/U$ was somewhat puzzling. From the physical reasoning given in the previous section, it was expected that at lower values of U_*/U, Reynolds number would have a dominant effect. There was really no reason for the reaeration variable to be independent of both Reynolds number and U_*/U. One possible explanation was that in the range of Reynolds number encountered, the dependence of k_2H/U on Reynolds number is very weak so that the change in k_2H/U over the one decade change in Reynolds number was not noticeable. Therefore, it was decided to make a few more experimental runs at a different Reynolds number range in order to obtain a clearer picture. Because the experimental facility was not capable of running at much higher discharges without going into supercritical Froude numbers, runs at lower Reynolds numbers were made. Three runs were made using the smooth bed and another three with a sand bed, with Reynolds number varying from 4.4×10^3 to 6.4×10^3.

Results of these experiments revealed that at the lower Reynolds number range, there indeed was a dependence of k_2H/U on Reynolds number. In fact, k_2H/U increased very rapidly with decrease in Reynolds number. These data points, together with the previous ones, are shown in a k_2H/U versus U_*/U plot in Figure 5, from which a much more logical picture of the behaviour of k_2H/U can be constructed. For a particular constant value of U_*/U, the value of k_2H/U is almost independent of Reynolds number until the Reynolds number goes below a certain value at which point k_2H/U increases with decreasing Reynolds number. The larger the value of U_*/U, the sooner would k_2H/U become independent of Reynolds number. The fact that the data at the low Reynolds numbers collapsed together suggests that at low Reynolds numbers, the curves all become asymtotic to a "smooth flow" curve as depicted in Figure 5. The picture is very similar to the Moody resistance diagram for flow in conduits in which the friction factor depends on relative roughness and Reynolds number.

Figure 6 shows k_2H/U plotted against U_*/U. The Reynolds number dependence is now apparent. Although there was no data for large Reynolds numbers, the lines were put in to complete the picture. Thus for a Reynolds number of, say, 10^6, the value of k_2H/U would increase very slowly with U_*/U until U_*/U equals to 0.06, when roughness becomes the dominant factor and k_2H/U increases rather rapidly with U_*/U. For smaller Reynolds numbers, this change in dependence would occur at a higher value of U_*/U. It is interesting to note that the points where the change in behaviour occurs correspond rather closely to the points on the Moody diagram in which flow resistance start to become independent of Reynolds number. For example, for Reynolds number equal to 2×10^4, the rapid increase of k_2H/U with U_*/U begins at U_*/U of about 0.09. From the Moody diagram, for Reynolds number equal to 2×10^4, the point where fully rough flow starts is $f= 0.065$, i.e. $U_*/U = 0.09$.

The dependence of the reaeration variable on U_*/U ard Reynolds number, described in Figures 5 and 6, explains why so many different equations of reaeration had been obtained in the past. Notwithstanding the errors in the measurement of k_2, experiments performed in different ranges of flow conditions would give results which depend very differently on the various hydraulic parameters. The fact is, of course, that the reaeration rate for open channel flows cannot be described by a single equation because of the dependence of the reaeration variable on both Reynolds number and U_*/U plus the change in the form of the dependence. In the case of natural streams, Reynolds numbers are usually large enough or friction factors high enough so that k_2H/U values would fall mostly on theoutside curve in Figure 6. However k_2H/U values for flow in artificial channels, sewer pipes, laboratory flumes etc., can be anywhere on the diagram.

There is one interesting fact which may not be apparent to the casual observer. Given two streams A and B, A being deeper and faster and B shallower and slower but both having the same relative roughness or U_*/U, their values of k_2H/U would be the same, both being in fully rough flow. For two locations a given distance x apart on either stream, the downstream DO deficit is equal to the upstream deficit times $\exp(-k_2x/U)$, considering only the atmospheric absorption of oxygen. Since the value of k_2/U for the two streams would vary inversely with their depths, stream B would have the smaller deficit at the downstream station. Therefore the increase in DO concentration is larger for the slower, shallower stream than for the faster, deeper stream. Churchill et al. (14) found that in their field experiments, in which water was released from reservoirs to the study reaches, the DO concentration always showed a U-shaped pattern, with lower DO in the centre and higher DO at the sides where velocities were lower and depths smaller.

Variations in DO were as high as 18%. The reason for this variation is now obvious.

For flows in the smaller Reynolds number ranges where the dependence on U_*/U is small the result is even more unexpected. For the same flow depths, a slower flow with smaller Reynolds number would have a larger value of k_2H/U, even if its relative roughness is somewhat smaller. Therefore, the DO increase from atmospheric absorption is larger for the quieter, less turbulent flow. For example, in the test with a sand bed with 3 centimeters depth and velocity of 36.6 centimeters per second, a parcel of fluid increased its DO concentration from 2 mg/litre to 2.28 mg/litre as it moved from the upstream to the downstream station, whereas in the test with a smooth bed at a velocity of 4.2 centimeters per second and the same depth, the DO concentration increased from 2 mg/litre to 2.48 mg/litre between the two stations. Although the reaeration coefficient k_2 was larger for the more turbulent flow, the amount of oxygen absorbed was less because it had less time for absorption.

Summary

From dimensional analysis and physical reasoning it was shown that the reaeration rate in open-channel flow could be studied by an experimental investigation of the dependence of the reaeration variable k_2H/U on U_*/U and Reynolds number. It is believed that the results obtained are quite accurate because the errors in measurement of k_2 had been minimized by using a 100 foot long test section and by the extra precautions taken in sampling and DO analysis.

The experimental results showed that for large relative roughness or large Reynolds numbers, the reaeration variable depends primarily on U_*/U and that for smaller values of Reynolds numbers and relatively smooth flow, Reynolds number has the greater effect on k_2H/U. The results resemble a Moody diagram type of plot showing that it is impossible to use one single equation to predict reaeration in all systems. However, for most natural streams, Reynolds numbers should be large enough so that k_2H/U depends only upon U_*/U.

The results also indicate that for natural streams with identical relative roughnesses, the slower, shallower stream would absorb more oxygen in a given length of reach than the faster, deeper stream. Also, in channels which are relatively smooth and small in Reynolds number, a quieter, smoother stream would absorb more oxygen in a given distance than a faster, rougher stream with the same flow depth.

Although no experiments at very large Reynolds numbers were possible in the laboratory flume, the trends indicated were quite obvious. The experimental results of course cannot be applied to flows in which Froude numbers approach supercritical or in which there are appreciable white waters or bubble entrainment.

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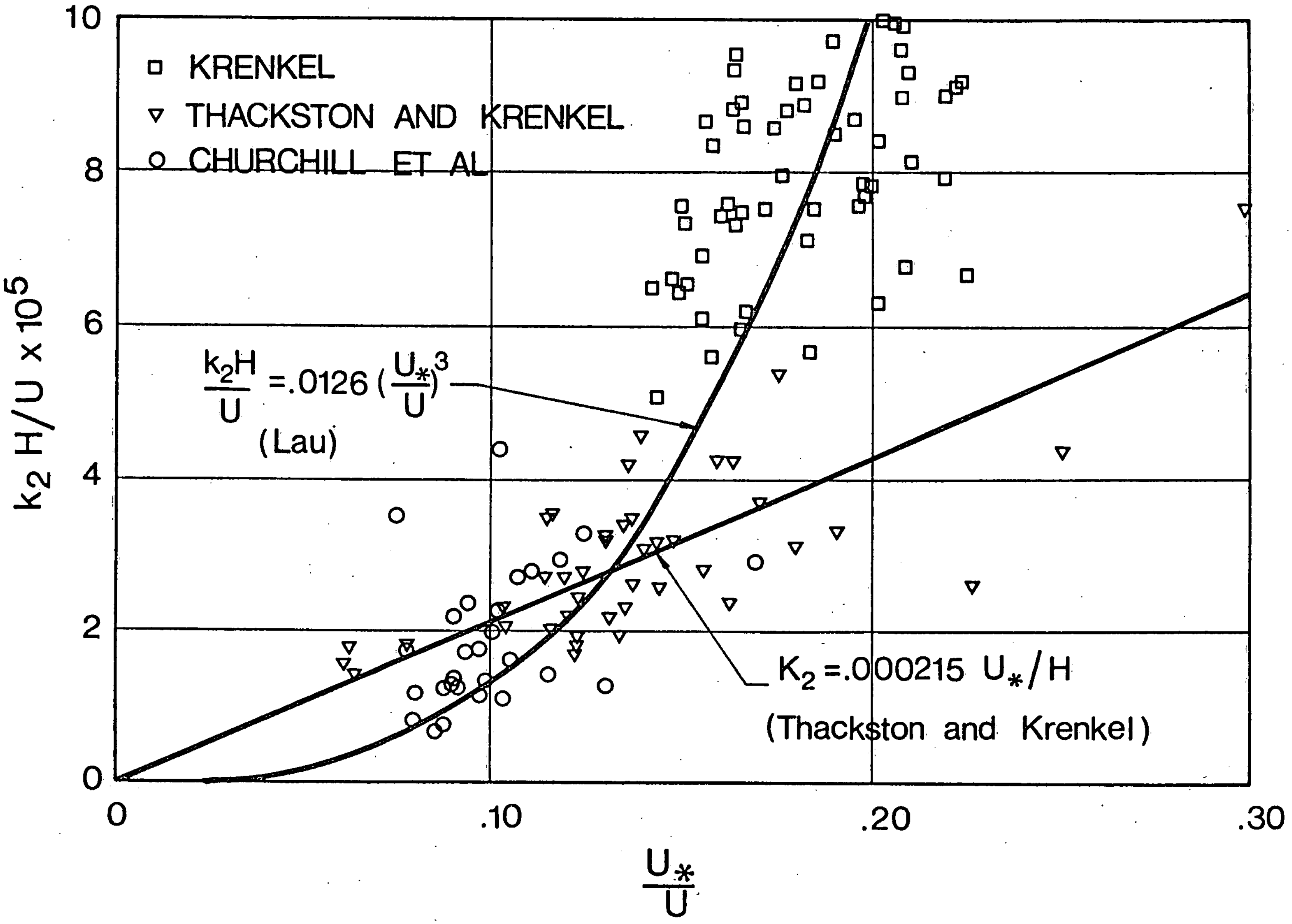

FIG. 1 Dependence of k_2H/U on U_*/U based on previous data

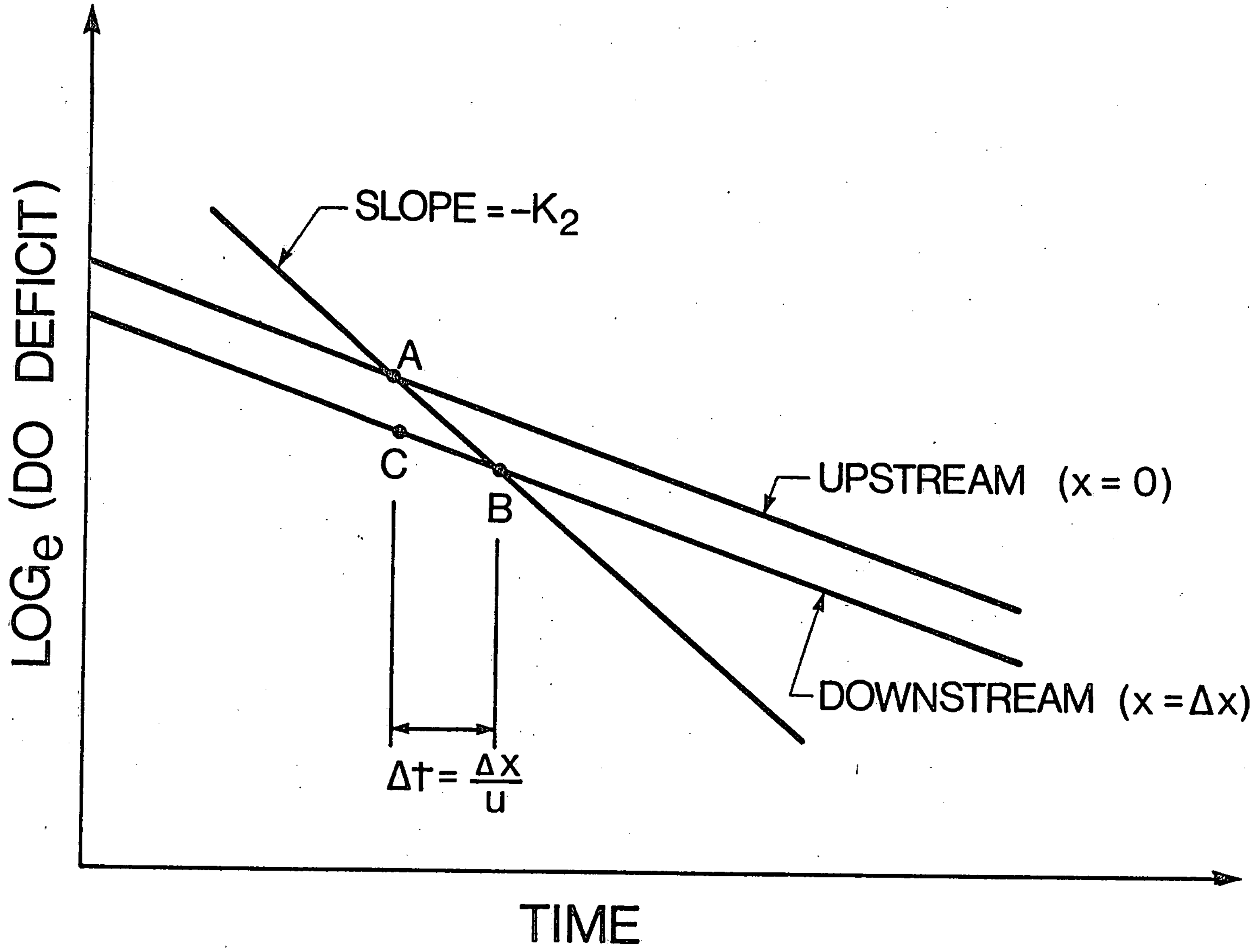

FIG. 2. Determination of the reaeration coefficient from recirculating flume data

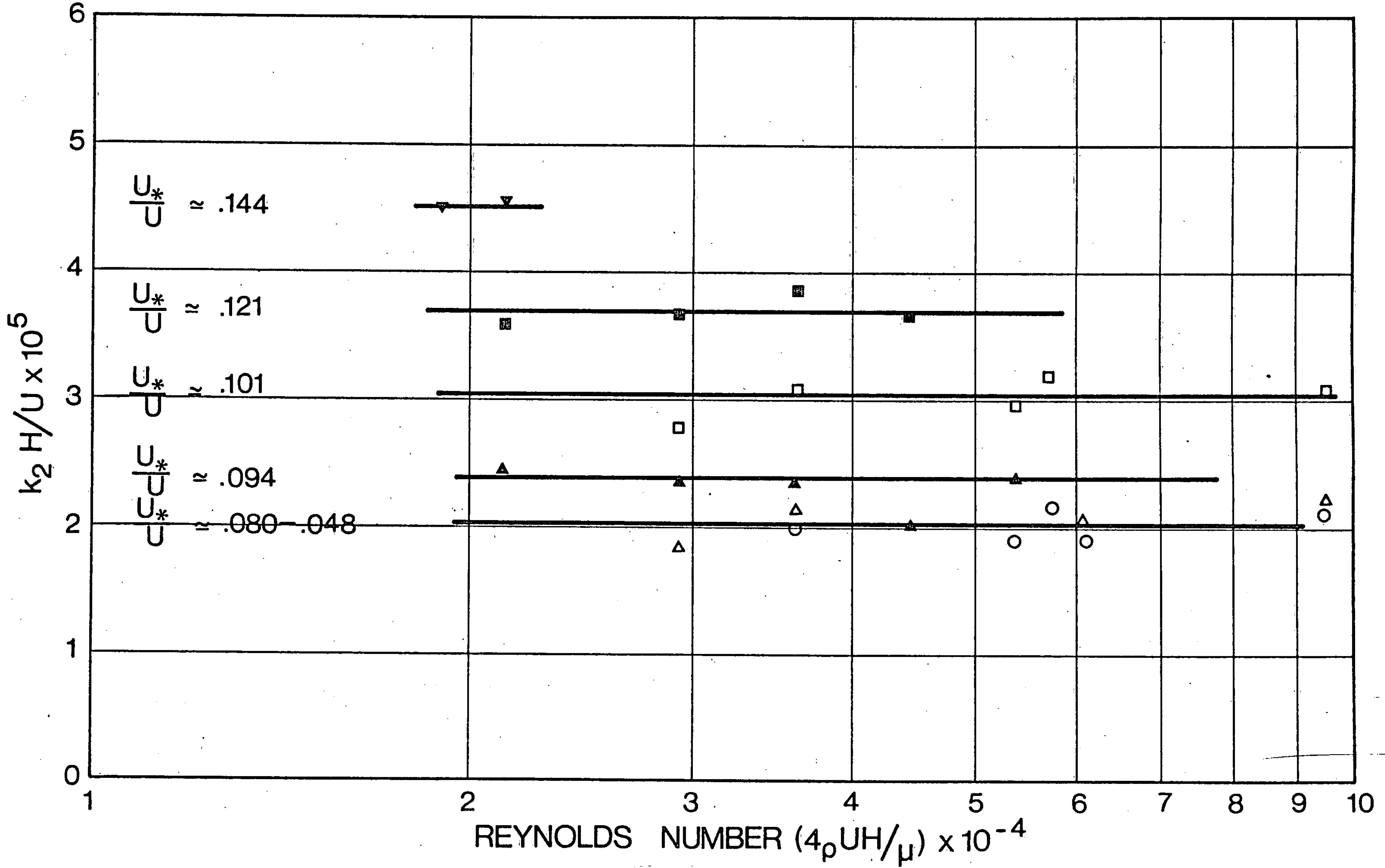

FIG. 3 Effect of Reynolds number on k_2H/U

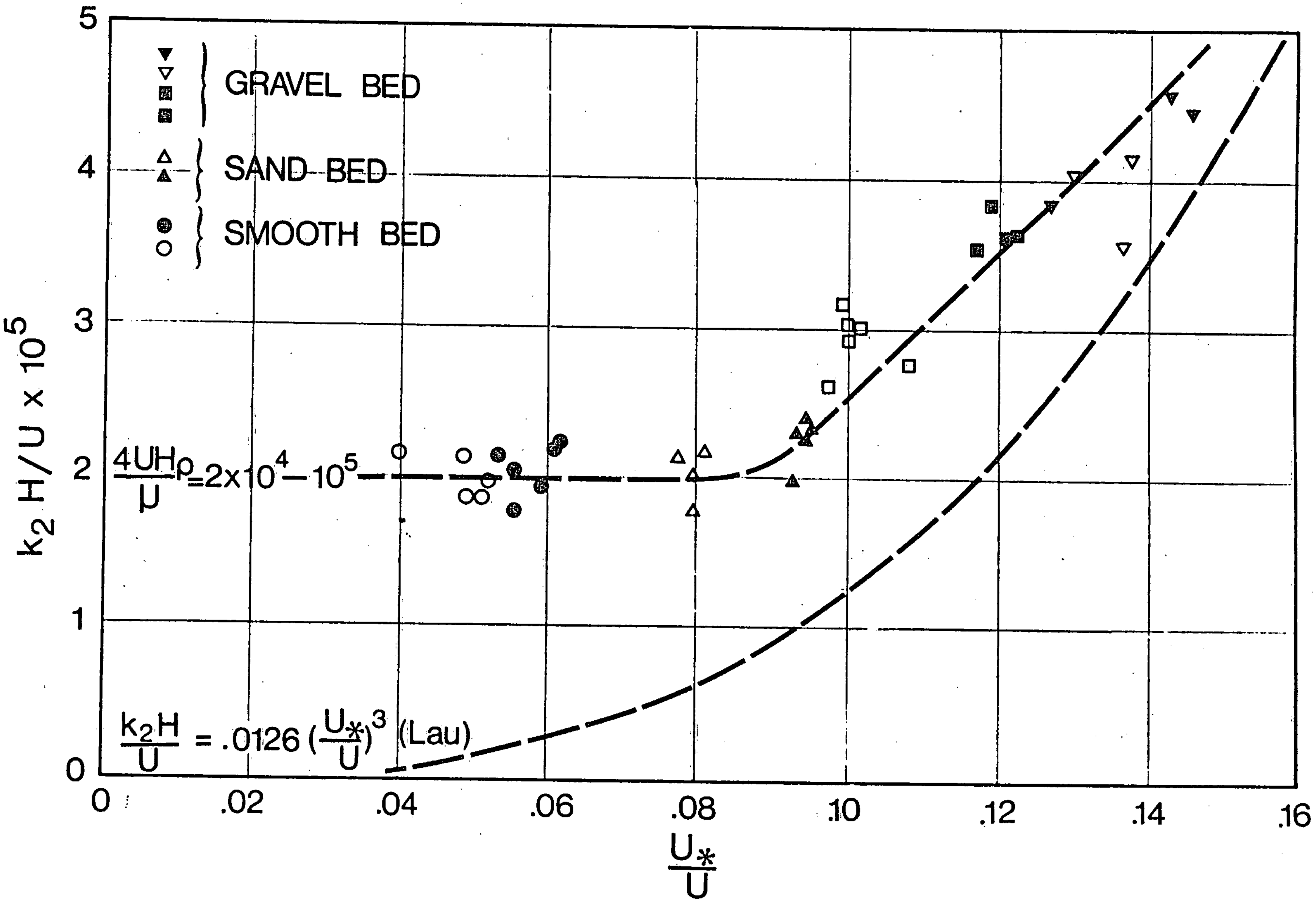

FIG. 4 Dependence of k_2 H/U on U_*/U

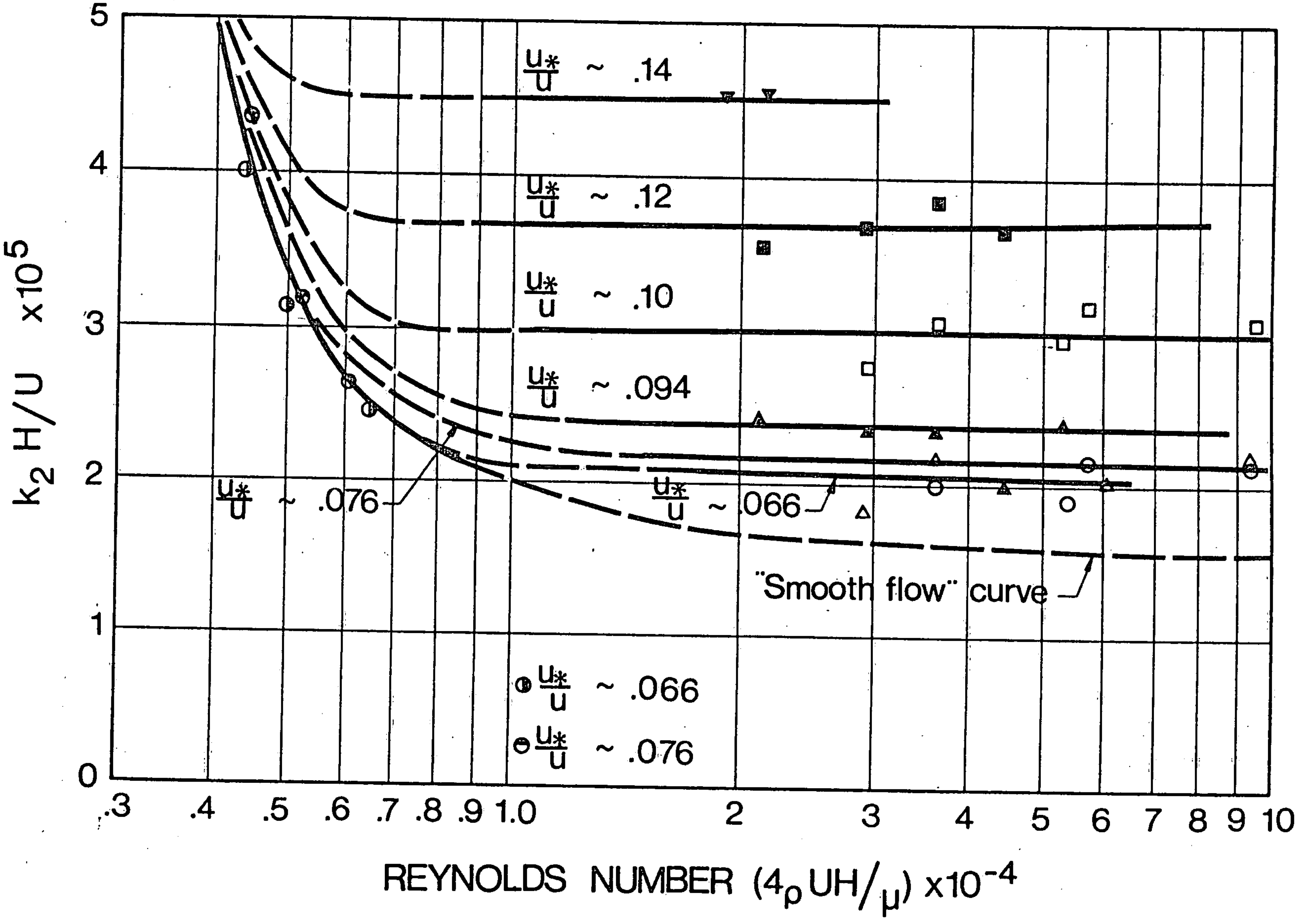

FIG. 5 Dependence of k_2H/U on Reynolds number, showing effects at low Reynolds number

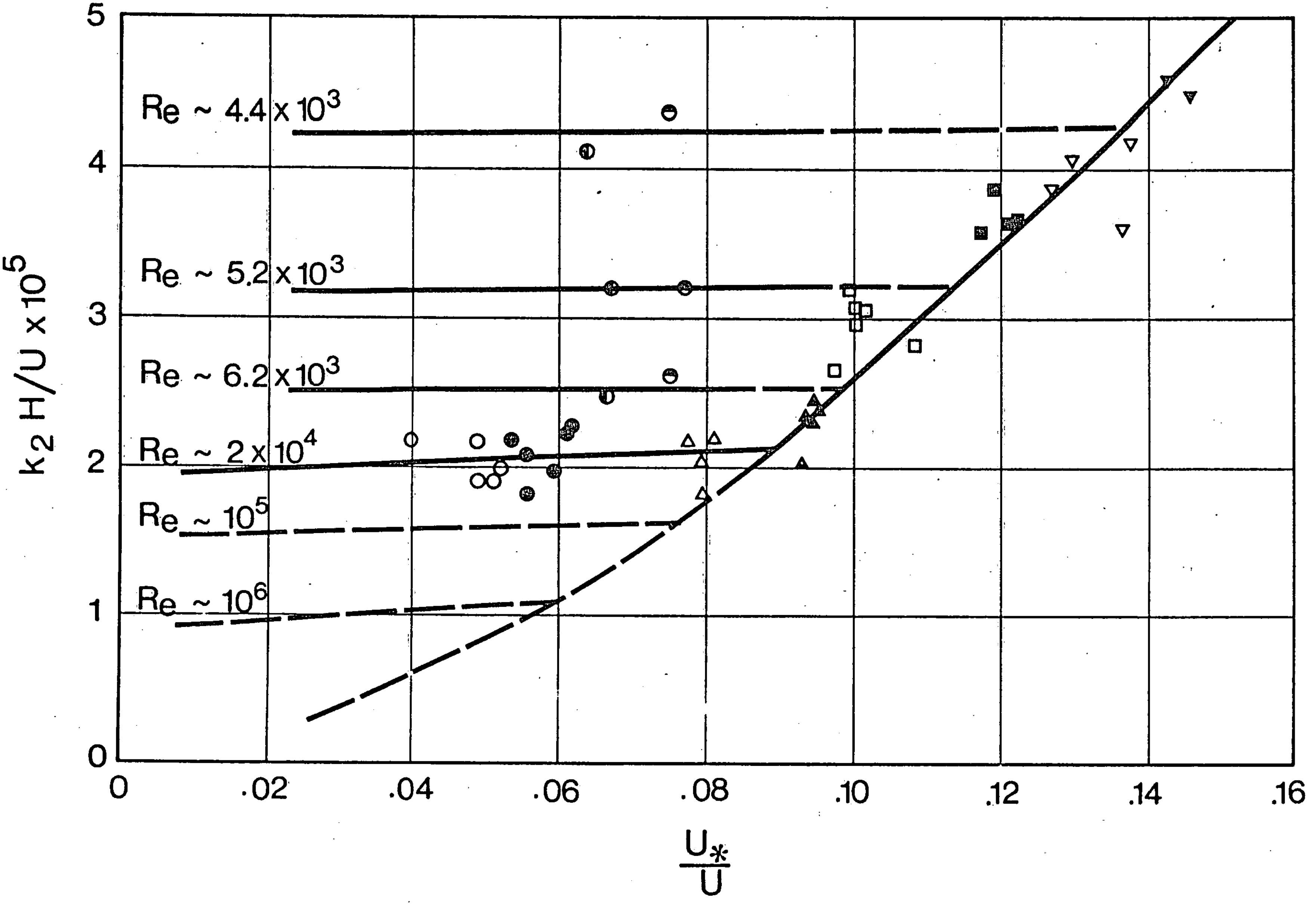

FIG. 6 Overall dependence of k_2H/U on U_*/U and Reynolds number