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STUDY OF THE MECHANICS OF
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FINAL REPORT

STUDY OF THE MECHANICS OF NON-NEWTONIAN FLUIDS-

FINAL REPORT

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FOREWORD

This report summarizes the results of a research program concerning several specific investigations of the mechanics of non-Newtonian fluids. The work was done between 26 June, 1963, and 26 December, 1968. Most of the results have been published in detail in the periodical literature and in LTV Research Center reports. Therefore, this report primarily serves to discuss the significant conclusions of the specific investigations and to present a comprehensive picture of the progress, as compared with the original objectives of the program.

Papers and reports referenced in this report are those which have been prepared by the staff of the LTV Research Center. Complete bibliographies of the work of others are included in the referenced papers and reports. The work of other investigators, including those participating in research programs for the National Aeronautics and Space Administration and the U. S. Navy, certainly contributed to this research program and should be acknowledged.

Certain peculiarities of the nomenclature used to describe non-Newtonian fluids should be noted here. For purposes of this report, "non-Newtonian" will be used to describe any fluid which has viscous properties different from that of a Newtonian fluid. "Drag-reducing" will be used to describe those fluids which produce less turbulent skin friction than a Newtonian fluid at the same flow condition. Thus, all drag-reducing fluids are non-Newtonian, but all non-Newtonian fluids are not drag-reducing.

ABSTRACT

The investigations of three aspects of the mechanics of non-Newtonian fluids are described. They are (1) correlation of data for turbulent flow of drag-reducing fluids and development of prediction techniques, (2) experimental studies of the effects of drag-reducing additives on the detailed characteristics of the turbulent shear layer, and (3) analyses of laminar boundary layer flow and transport properties of the fluids of interest.

The most significant results include: considerable pressure drop and velocity profile data for solutions of several drag-reducing additives in turbulent pipe flow; a correlation of the data in terms of two easily-determined fluid properties, enabling skin friction to be predicted for arbitrary turbulent flows; observations that the significant effect of additives on turbulent shear characteristics is to thicken the viscous sublayer, increase the turbulence intensity in the turbulence production region near the wall, and affect the wall shear stress only when the additive is present in the wall region; observations that the effect of roughness in flows of drag-reducing fluids is consistent with the physical concept of a wall phenomenon and is predictable with a modified roughness function; heat transfer in drag-reducing fluids is predictable through the use of the Prandtl-Reynolds analogy; and the conclusion that all drag-reducing solutions tested showed evidence of supporting normal stresses, with no dependence on the age of the solution.

Toward the end of this reporting period a symposium devoted to discussion of research on viscous drag reduction was held at the LTV Research Center. A summary of the results of that meeting is also given.

INTRODUCTION

The primary objective of this research program has been to develop methods for predicting the flow of non-Newtonian fluids, especially that of aqueous polymer solutions which are drag-reducing. This objective has required obtaining considerable experimental data and extensive analysis of the data and comparison with data for Newtonian fluids. It has required the study of a number of specific, related problems in order to complete the investigation. The study began with theoretical analyses of laminar flow of purely viscous non-Newtonian fluids, as well as with experimental studies of drag-reducing polymer solutions. Then the objective was narrowed to that of predicting turbulent flow of drag-reducing fluids.

This latter objective was chosen for a very practical reason. It was known that very small amounts of certain polymer additives, when added to a solvent, change the momentum transport drastically, resulting in reduced skin friction (up to 80 percent reduction). Such a large effect has many potential applications in fluid systems. Although many of the rheological and chemical aspects of this phenomenon were of interest, it seemed at the time that a basic investigation of the fluid mechanics of the phenomenon would be required before any useful application could be made.

It was also of interest to study the detailed effects of drag-reducing fluids on the characteristics of turbulent shear flow. This provides a different view of one of the great unsolved problems of fluid mechanics and should eventually contribute to direct analytical treatment of turbulent shear flows.

The effort may be divided roughly into three broad types: (1) obtaining and analyzing data in order to provide a basic relation between the flow and fluid properties in order to make predictions for arbitrary turbulent flows of drag-reducing fluids; (2) experimentally investigating detailed effects on the turbulent shear flow, such as turbulence measurements and local injection of additive solutions; and (3) experimentally and theoretically investigating laminar flow and the transport properties of the fluids of interest. The following section discusses each specific task which contributed to the overall objective.

DISCUSSION

Data Correlations and Prediction Techniques for Turbulent Flow of Drag-Reducing Fluids

Experimental Studies of Skin Friction in Turbulent Pipe Flow of Drag-Reducing Fluids in Smooth Pipes. Turbulent pipe flow experiments have been done with aqueous solutions of four types of additives - guar gum (J-2P), sodium carboxymethylcellulose (CMC), a copolymer of poly(acrylamide) and polyacrylic acid (P-295), and Polyacrylamide (PAM). The purpose of the experiments was to obtain sufficient information about the dependence on various flow and fluid parameters to correlate the data and thus make predictions for arbitrary flows.

The first experiments were done with relatively concentrated solutions of guar gum. These were reported in Reference 1. The significant results were as follows:

(a) Significant wall shear stress reductions were found for concentrations from 500 to 4000 parts per million.

(b) Turbulent friction factors for these solutions depended upon pipe diameter, as well as on Reynolds number.

(c) Significant shear stress reductions were found for a solution (concentration) which had no shear-thinning, indicating that something other than the purely viscous properties was affecting the turbulent transport process or sublayer stability.

(d) Velocity profile data showed the viscous sublayer to be thickened. The slope of the law of the wall velocity profile was greater than that for Newtonian fluids, but approached the slope for Newtonian fluids with decreasing concentration.

Subsequent experiments were performed with CMC at a concentration of 500 parts per million[2]. This solution had no appreciable shear-thinning and was a moderately effective drag reducer. It was noted during these and later experiments that there was no tendency of the additive to change the transition Reynolds number. The turbulent friction factor data showed a diameter effect similar to that for guar gum. The law of the wall velocity profiles showed a shift, parallel to that for water, which increased in magnitude with increasing Reynolds numbers.

These observations were used to determine the correlation of velocity profile and friction factor data with wall shear stress, which is described in the following section. After the early experiments had been run in a temporary test set-up, a pipe flow facility designed for the testing of polymer solutions was constructed by the LTV Research Center.

Following initial check-out of the facility, a series of tests of a CMC solution in five different pipe sizes ranging from 1/8 to 1.5 inches in diameter were used to evaluate the correlation. The data, presented in Reference 3, fit the correlation very well, giving experimental justification for the technique.

The facility has since been used to determine the parameters of the correlation as a function of concentration for several different additives. A summary of those results is presented in Figures 1 through 3, in which α, the parameter indicating the degree of drag reduction, is plotted versus concentration for P-295, PAM and CMC. Figures 4 through 6 are plots of $u_{*_{cr}}$, the shear velocity at which the onset of drag reduction takes place, versus concentration for the same additives. Data for different diameter pipes are shown to indicate the validity of the correlation. It can be seen for data of the more effective additives, i.e., P-295 and PAM, that the correlation does not hold for concentrations above a certain value in the pipe sizes used. That is, for concentrations which give values of α above about 20, the measured values of α and $u_{*_{cr}}$ are no longer the same in different pipe sizes. This is believed to be due to a large transition layer thickness relative to the pipe diameter and a loss of the law of the wall form of the velocity profile, which violates the criterion for the correlation. This is simply a limit on the type of solution which can be tested in a given pipe size when data for generalization are desired.

Thus, through use of the correlation, these data can be used to predict flow of these additives in many cases of turbulent flow. In addition, other simple pipe flow tests, in which only pressure drop and flow rate are measured can be used to determine the flow properties of other additives.

Correlation of Data for Turbulent Flow of Drag-Reducing Fluids in Smooth Pipes. Physical interpretation of the turbulent velocity profile and friction factor data for drag-reducing fluids led to an attempt to correlate drag-reduction effects with wall shear stress[4]. In particular, the magnitude of the parallel shift in the law of the wall profile was plotted versus the shear velocity, u_*, which is the square-root of wall shear stress divided by fluid density. The shift was found to be a unique function of u_* for flows of each of several additive solutions in various pipe sizes.

The function was identical to that for Newtonian fluids below some critical shear stress. That is, there was no effect of the additives below the critical shear stress. Above the critical shear stress, the shift in velocity profile increased with increasing shear stress. This also explained the diameter effect, since the decrease in friction factor would be greater in small pipes than in large pipes at the same Reynolds number, owing to the difference in shear stress at the same Reynolds number.

A semi-logarithmic function was fitted to the velocity profile data and was incorporated into the form of Prandtl's universal law of friction. The result was an expression for friction factor in terms of Reynolds number (based on viscosity at the wall); α, the parameter indicating the degree of drag reduction; and $u_{*_{cr}}$ the shear velocity for the onset of drag reduction.

The result of this analysis was that the properties of a fluid can be completely described for purposes of predicting turbulent flow by determining α and $u_{*_{cr}}$. This can be done in a simple pipe flow apparatus, requiring only that pressure drop and flow rate be measured. Thus, a simple pipe flow set-up can be used as a turbulent flow rheometer and the problem of the determination of the basic fluid properties which cause the drag reduction becomes somewhat secondary if prediction of wall shear stress is of primary importance.

Prediction of Heat Transfer in Turbulent Flow of Drag-Reducing Fluids. Since one possible application for drag-reducing polymer additives is for liquid heat exchanger systems, it was of interest to investigate the heat transfer properties of such fluids. An analysis was done to extend the analogy between energy and momentum transport for turbulent pipe flow of purely viscous fluids to include drag-reducing, non-Newtonian fluids[5]. The analysis includes the effects of sublayer thickening, as given in the correlation of Reference 4.

The use of the friction factor correlation with the heat transfer analogy makes it possible to predict heat transfer rates from simple measurements of pressure drop and flow rate. This again shows the practical use of a simple pipe flow apparatus as a turbulent flow rheometer for drag-reducing fluids.

Some recent experimental data for two effective drag-reducing fluids and for water were compared with the predicted heat transfer rates, and the mean deviation in Nusselt number is found to be +8.5% for all of the data. The heat transfer analysis predicts a reduction in Nusselt number accompanying a reduction in friction factor for a given Reynolds number and for Prandtl numbers greater than one.

Effects of Surface Roughness on Turbulent Flow of Drag-Reducing Fluids. A study of the flow of a drag-reducing fluid over a rough surface was made with two objectives in mind; to see if the effects of surface roughness could be taken into account in the analytical treatment of turbulent shear flows of drag-reducing fluids analogous to the methods of Newtonian fluid mechanics, and specifically, to find what loss in ultimate drag-reducing effectiveness might be caused by surface roughness. The results of the study were reported in Reference 6.

Experiments were performed in a 3/4-inch pipe having interchangeable sections with internal threads for roughness. The threads were cut in the form of V-shaped grooves having sharp edges and a 90° included angle between faces with each face being at 45° to the flow direction. Roughness heights of 2.1, 2.8, and 5.6 percent of the pipe radius were used. A 31 PPM solution of P-295 in water was used as the fluid.

The analytical expression for the law of the wall velocity profile was modified to include the sublayer thickening effects of the drag-reducing additive. From this relation an expression for a roughness function for drag-reducing fluids was derived which allowed calculation of the roughness function from friction factor-Reynolds number data and the drag reducing fluid parameters, α and u_{*cr}.

The major conclusions to be drawn from these experiments are as follows:

(a) The onset of roughness effects is the same for Newtonian and drag-reducing fluids, if the onset of roughness precedes the onset of drag reduction. Also, the drag-reduction onset is the same in smooth and rough pipes for drag-reducing fluids if flow is not in the fully rough regime.

(b) The roughness function, as defined for drag-reducing fluids, is greater than the Newtonian roughness function beyond the drag-reduction onset and is dependent on α and u_{*cr} in addition to the roughness height.

(c) The threshold of fully rough flow is found to occur at higher Reynolds numbers in drag-reducing fluids than in Newtonian fluids in accordance with predictions based on the sublayer thickening effect of the additive.

(d) Friction factors are less for the drag-reducing fluid in the roughness transition regime than for Newtonian fluids and can actually be less than for smooth pipe Newtonian flow if the roughness is small such that drag-reduction onset precedes the onset of roughness effects. The friction reduction diminishes as the fully rough regime is approached and there is a strong indication that no friction reduction will occur beyond the fully rough threshold, although this last point will require further experiments for confirmation.

(e) A roughness function for drag-reducing fluids can be used to predict friction factors below the onset of drag reduction and above the threshold of fully rough flow. The same function shows a smooth transition between the two limits.

(f) Measurements of friction reduction in a smooth pipe section downstream of the roughness section confirmed that no mechanical degradation of the fluid occurred due to the surface roughness.

Effects of Drag-Reducing Additives on the Characteristics of Turbulent Shear Flow

Local Effects of Drag-Reducing Additives Determined by Injection of Additive Solutions. The observed effects of drag-reducing additives in turbulent pipe flow suggest that the significant changes in a turbulent shear layer due to additives occur in the viscous sublayer region. Furthermore, it was hypothesized that the additives need be present only near the wall and not in the turbulent core to realize friction reduction. As a test of this hypothesis, injection of solutions into a turbulent pipe flow of water was performed to determine friction effects for the conditions of drag-reducing additives present only near the wall and only in the turbulent core. These experiments were reported in detail in Reference 7.

Wall injection was through a 1/8-inch circumferential slot set at a ten-degree angle to the pipe wall. Core injection was through a 5/16-inch diameter tube set at the pipe centerline. The pipe test section was 1.5-inch i.d. plexiglas tubing. A constant water flow was maintained through the test section at a pipe Reynolds number of 85,000. The following fluids were used in the injection experiments: (1) water, (2) a 1000 PPM by weight solution of a guar gum (J-2P) in water, (3) a 100 PPM by weight solution of a copolymer of polyacrylamide and polyacrylic acid (P-295) in water, and (4) a solution of corn syrup and water having a viscosity about 5 times that of water. Injection rates were varied from about 1 percent to 5 percent of the total mass flow through the pipe. This can be compared to the mass flow in the viscous sublayer of about 3 percent of the total mass flow. Dye added to the injectants showed diffusion rates for all fluids to be essentially the same. Diffusion from the wall for the case of wall injection and toward the wall for centerline injection was relatively gradual requiring approximately 20 and 12 pipe radii respectively before uniform distribution was reached.

Injection tests with water and with diluted corn syrup were made to determine the effects on skin friction of the jet flow and fluid viscosity separate from the effects of the additives. Net friction reduction with the additives was determined from direct comparisons with water injection results. Comparisons were also made with friction factors calculated for homogeneous additive solutions matching the concentrations estimated in the injected flows. The significant results and conclusions are as follows:

(a) The effects of the injection apparatus and jet flows are small compared to the drag-reduction effects.

(b) Dilute solutions of drag-reducing fluids in turbulent shear flow cause appreciable reduction of local skin friction when the drag-reducing additives are only present near the wall, and conversely, drag-reducing fluids injected in the turbulent core do not reduce skin friction until diffusion has carried them into the wall region.

(c) For wall injection of drag-reducing fluids with viscosity greater than that of water the observed friction reduction is more than that predicted based on the viscosity of the drag-reducing fluid but close to the predicted value if the viscosity of water is assumed. Or, in other words, the increased viscosity of the injected fluid does not seem to diminish the friction reduction.

(d) Assuming typical turbulent diffusion, the predicted friction reduction for a fully diffused injectant in wall injection is less than that actually realized, whereas the friction reduction is about as predicted far downstream of centerline injection. This implies that the diffusion of the injectant out of the wall region is relatively slow and the additive concentration in this region remains sufficiently high for significant friction reduction over an appreciable distance. Further experiments would be needed to check this point, however.

Effects of Drag-Reducing Fluids on the Longitudinal Component of Turbulence in a Turbulent Shear Flow. In seeking to understand the drag-reduction phenomenon caused by certain polymer additives it is desirable to examine as many aspects of drag-reducing fluid flow as is practical. Since friction reduction seems to be exculsively associated with turbulent shear flow a natural extension of mean flow property studies is an investigation of the effects of drag-reducing additives on turbulence structure. To date this laboratory has made experimental studies of turbulence intensity and spectral energy distribution in turbulent pipe flow for three drag-reducing fluids; a 500 PPM solution of CMC in water, a 31 PPM solution of P-295 in water and a 100 PPM solution of P-295 in water. The results of these experiments have been reported in References 6 and 8. All of the turbulence measurements were made with piezoelectric crystal instrumented total pressure probes which were developed by this laboratory during this program.

The first turbulence measurements were made in a 500 PPM solution of CMC in water, a moderately effective drag-reducing fluid giving a maximum friction reduction of about 30 percent. Turbulence intensity at the centerline of a 3/4-inch diameter pipe was measured over a range of Reynolds numbers and compared directly with similar measurements in water. Turbulence intensity profiles across the pipe diameter were also measured at several Reynolds numbers and spectral data were measured at the pipe centerline and near the wall.

In general there were no strong effects found in the turbulence structure due to the CMC. As an extension of the study similar measurements were made in 31 PPM and 100 PPM solutions of P-295 in water, a much more effective drag-reducer than CMC, giving maximum friction reductions of 60 and 80 percent for the two concentrations. Some significant changes in turbulence structure were found in the P-295 solutions. The major results and conclusions of the turbulence experiments may be summarized as follows:

(a) Turbulence intensity at the pipe centerline is virtually the same for the 500 PPM CMC solution as for water over the range of Reynolds number tested. For the 31 PPM solution of P-295 the turbulence intensity at the pipe centerline for high Reynolds numbers is about 15 percent less than for water, and at low Reynolds numbers about 20 percent greater than for water. The centerline turbulence intensity for the 100 PPM solution of P-295 showed strong changes with Reynolds number, being approximately equal to that for water at high Reynolds numbers and increasing to three times that of water at the lower Reynolds numbers.

(b) Turbulence intensity profiles show the 500 PPM CMC data to be in fair agreement with water data throughout the flow except very near the wall where at high Reynolds numbers the CMC data appear to increase slightly. The 31 PPM P-295 data show the turbulence intensity to be close to that of water throughout the turbulent core but near the wall an obvious increase at high Reynolds number and decrease at low Reynolds number is found. The 100 PPM P-295 data show the turbulence intensity to be close to that of water at high Reynolds numbers and much higher than for water at low Reynolds numbers throughout the turbulent core, but in both cases a strong reduction in intensity is found near the wall.

(c) No appreciable differences in turbulence spectra were found between water and any of the drag-reducing fluids. There was some indication that the turbulent energy in CMC was shifted slightly toward higher wave numbers but this was not apparent in the P-295 solutions. Determination of macroscale and microscale from the turbulence spectra showed moderate differences between water and the drag-reducing fluids with no apparent pattern to the changes.

(d) In general, it can be said that both increases and decreases in turbulence intensity relative to Newtonian values are possible in drag-reducing fluids and are dependent on concentration, Reynolds number, and shear rate. This behavior suggests a possible elastic phenomenon which controls the turbulence structure instead of a simple dependence of friction reduction on turbulence reduction. The limiting case of very dilute solutions at conditions of large drag reduction is characterized primarily by a slight reduction in intensity in the turbulent core and an increase in intensity in the buffer or "turbulence production" region.

Analyses of Laminar Boundary Layer Flow and Transport Properties of Non-Newtonian Fluids

Theoretical Analyses of Laminar Flows of Non-Newtonian Fluids. Since viscometric measurements done early in the program showed that the polymer solutions of interest were "shear-thinning"; i.e., the apparent viscosity decreased with increasing shear rate, it was of interest to investigate laminar flows of this type of fluid. The "power-law" relation between shear stress and shear rate was chosen to describe the fluid, since it adequately describes experimental data for most shear-thinning fluids.

The boundary layer equations for power-law fluids were investigated for the purpose of obtaining all possible conditions for which similar solutions exist. Both steady and unsteady flows were included. The similar solutions obtained represent, in all cases, generalizations of boundary layer flows of Newtonian fluids. The solutions were discussed with respect to application to physical flows. Some of the more familiar flows represented are: steady flow over a flat plate, a wedge, and a stagnation region; steady flow in a convergent or divergent channel; and impulsively started flow over an infinite flat plate and a semi-infinite flat plate. These results were published as a National Aeronautics and Space Administration Technical Note.[9]

An extension of this paper was published in the AIAA Journal.[10] A similar solution is presented for the case of two-dimensional, incompressible, laminar boundary layer flow on a flat plate of finite extent which is impulsively changed to a constant velocity. In addition, numerical solutions were found for the special case of boundary layer flow on an infinite flat plate suddenly put into motion.

In order to determine the feasibility of experimentally determining the elastic properties of drag-reducing fluids, a theoretical study of various flow configurations and rheological models of viscoelastic fluids was undertaken.[11] The Jeffreys Model was chosen to represent the rheological properties of the liquid and calculations of the response characteristics in a rotating disk apparatus were done.[12] The calculations pointed out the difficulties of detecting viscoelastic effects in the very dilute solutions of interest for drag reduction. The experimental work to measure elastic properties is described in a later section.

Fluid Properties of Drag-Reducing Fluids. It has been recognized for several years that the liquid solutions of interest have not been completely described rheologically. This has been difficult to accomplish experimentally, particularly with regard to the elastic properties. Even if the elastic properties could be obtained, they would be of dubious value at this time, since the mechanism of production, transport and dissipation of turbulence in a shear layer is not well understood, even for Newtonian fluids.

For this reason the complete characterization of elastic properties of fluids of interest has not been pursued since the early theoretical studies of References 11 and 12. Instead, the correlation of the parameters, α and u_{*cr}, with known properties of the various additives, has seemed to be a more useful approach.

It was necessary to determine the viscosity of some of the liquids at the high shear rates which are encountered in turbulent flow, since some of the liquids used early in the program were highly shear thinning. Extensive measurements were made in a Merrill-Brookfield high shear-rate viscometer and were reported in References 1 and 13 . Fluids used in more recent experiments have little or no shear-thinning, as well as little or no change in viscosity from the pure solvent. Thus, viscosities can be determined in a relatively simple precision viscometer for these fluids.

One of the early results of correlations of the turbulent skin friction data was that the significant viscosity for generalizing the flow relations is the viscosity at the wall. This is significant for fluids which are highly shear-thinning, and thus requires accurate determination of viscosity over the range of shear rates of the flow.

In order to gain some information concerning the existence of normal stresses in the flow of drag-reducing fluids an experiment was performed to infer normal stress from the measurement of the thrust of a laminar jet, using the fluids which have been commonly tested in other phases of this program. The detailed results of this effort will be presented in a forthcoming report from this laboratory. The experiments and preliminary data analysis will be summarized here.

The reasoning upon which the jet-thrust technique is based is that the net thrust exerted by a cylindrical jet of fluid issuing from a round tube is related to the difference between the momentum flux of the fluid as it leaves the tube and any tensile stresses with which the fluid in the jet pulls on the fluid still in the tube. It can be shown that the normal stress in the axial direction (evaluated at the wall shear rate) can be determined from measurements of the thrust of a fluid jet as a function of the mean velocity of the fluid in the tube. This effect will be seen as a difference in the jet thrust obtained at a given flow rate from a particular tube for fluids which do support normal stresses as compared with fluids that do not.

Four drag-reducing fluids were tested for normal stress effects and compared to water. The four fluids were (1) a 500 PPM solution of CMC in water, (2) a 1000 PPM solution of J-2P in water, (3) a 100 PPM solution of P-295 in water, and (4) a 100 PPM solution of poly(ethylene oxide) (WSR-301) in water. The fluids were pumped through a 0.010-inch diameter tube and the jet allowed to impinge on a parallel bar linkage such that all axial momentum was taken out by the linkage. The thrust of the jet on the parallel bar linkage was transferred to a very sensitive null-type force balance and the fluid drainage from the apparatus was collected for an interval of time to determine the mass flow rate of the jet. The force balance was a modification of a design used extensively in this laboratory for skin friction measurements in low speed boundary layer studies. This balance is capable of resolving forces as small as 10^{-6} lb with an accuracy of ±1%.

The thrust of water jets was measured first and the data matched well with the linear relation for thrust versus the square of the flow rate. This was checked over a tube Reynolds number range of 450-1650. A slight shift in the curve due to surface tension was noted which checked closely with the calculated effect. The friction velocity, u_*, varied from about 0.6-1.4 feet/sec, which in every case exceeded $u_{*_{cr}}$. Estimates of experimental uncertainties gave values of about .5% for flow rate, 2% for diameter, and 2% for thrust measurements.

Thrust measurements with all of the drag-reducing fluids were also linear and all showed some reduction in thrust compared to water data, the reduction increasing linearly with the square of flow rate. Measurements were made with freshly mixed samples of all fluids and with aged samples of all fluids ranging up to 10 days old. The P-295 solution was also tested after being run at high flow rates through the pipe flow facility 15 times. There was no noticeable degradation effect for any of the fluids due to aging and also no degradation due to shear in the P-295.

The amount of thrust reduction, which indicates the magnitude of the normal stress, varied from fluid to fluid approximately in the same order as the drag-reducing effectiveness of the fluids. At the maximum flow rates the thrust reduction, as compared with α and $u_{*_{cr}}$, was as follows:

SOLUTION	THRUST REDUCTION, %	α	$u_{*_{cr}}$, FT/SEC
500 PPM CMC	2	6.5	0.23
1000 PPM J-2P	5	24.4	0.21
100 PPM P-295	6	22.8	0.1
100 PPM WSR 301	7	36.0	0.049

Measurements were also attempted in a 0.065-inch diameter tube in order to test for normal stresses at lower shear rates over the same Reynolds number range. These tests were inconclusive due to large surface tension effects at the tube exit causing erratic flow behavior.

Further tests to characterize the other two normal stresses do not seem to justify the experimental complexity required, since the primary benefit of normal stress measurements at this time is to record the presence of normal stresses, rather than to characterize the fluids in detail.

At the present time calculations of axial normal stress are being made using the thrust data. These results will be in the forthcoming report. In summarizing, the tentative conclusions at this point are as follows:

(a) The thrust of small laminar jets can be measured with sufficient accuracy to test for normal stress effects.

(b) All of the drag-reducing fluids tested exhibit thrust reductions compared to similar tests with water.

(c) The magnitude of the thrust effects varies with the drag-reducing effectiveness of the fluids.

(d) Aging and shearing do not seem to change the thrust effect.

Symposium on Viscous Drag Reduction

On 24 and 25 September, 1968, a symposium concerning the subject of viscous drag reduction was held at the LTV Research Center. It was jointly sponsored by the National Aeronautics and Space Administration, The Office of Naval Research and the Naval Ship Research and Development Center; and was hosted by the LTV Research Center.

The subject of turbulent skin friction reduction was a subject of major interest at the symposium and a paper on work done under this program was presented. This paper will be published in the symposium proceedings[6], which will be available during the first quarter of 1969.

Boundary layer transition and theoretical considerations of turbulent boundary layers in general were also subjects of major interest at the meeting. There was considerable discussion of all of the papers.

Approximately 100 research workers in these areas of fluid mechanics attended the meeting. Attendance was by invitation in order to ensure an interested, participating group. The attendees represented most of the major government and industrial laboratories and universities in this country which are interested in these problems, as well as several representatives of other free western countries.

CONCLUSIONS

The major conclusion of this study is that useful engineering predictions of the turbulent flow of drag-reducing non-Newtonian fluids can now be made. This includes prediction of skin friction, heat transfer, and wall roughness effects. In addition, considerable information about the effects of drag-reducing additives on turbulence and mean flow properties in a shear layer, and the effects of local injection of additive solutions has been obtained. These effects will continue to be of interest as the effort to determine the mechanism of drag reduction continues. This is also true of the observations of normal stresses in drag-reducing additives.

The mechanism of drag reduction with polymers is not understood, as yet. And while work should continue toward providing a basic physical explanation for the phenomenon, it can be said that there is now sufficient understanding to predict the flow of drag-reducing fluids, with the same types of empirical techniques used for predicting turbulent flow of Newtonian fluids.

Thus, attention can and should be turned to the applications of drag reduction. These applications include reduction of losses in various types of constrained flows and reduction of skin friction for external boundary layer flows.

In addition, anomalous fluid mechanics effects of these polymer additives other than skin friction reduction have been discovered. Some of these are: reduction of transmitted and radiated turbulent boundary layer noise, delay of cavitation onset, and delay of laminar separation onset. There are useful applications for these effects and they should be investigated, primarily through experiments.

In summary, there are many useful effects of non-Newtonian polymer solutions, some of which are ready for application and some of which bear further investigation.

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1. Wells, C. S., "On the Turbulent Shear Flow of an Elastico-Viscous Fluid", Presented at the First Aerospace Sciences Meeting, January 20-22, 1964, New York, AIAA Preprint No. 64-36.

2. Meyer, W. A., "Study of the Mechanics of Non-Newtonian Fluids", Presented at the First Annual Meeting of Participants in the NASA Research Program in Non-Newtonian Fluid Mechanics, February 9, 1965, Houston.

3. Meyer, W. A., "Study of the Mechanics of Non-Newtonian Fluids", Presented at the Second Annual Meeting of Participants in the NASA Research Program in Non-Newtonian Fluid Mechanics, December 6, 1965, Philadelphia.

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5. Wells, C. S. and J. G. Spangler, "Effects of Local Injection of a Drag-Reducing Fluid into Turbulent Pipe Flow of a Newtonian Fluid", Presented at the Fourth Winter Meeting of the Society of Rheology, February 6-8, 1967, Santa Barbara.

6. Wells, C. S., "Turbulence Measurements in a Drag-Reducing Non-Newtonian Fluid", Presented at the Symposium on Mechanics of Rheologically Complex Fluids, Society of Petroleum Engineers, December 15 and 16, 1966, Houston.

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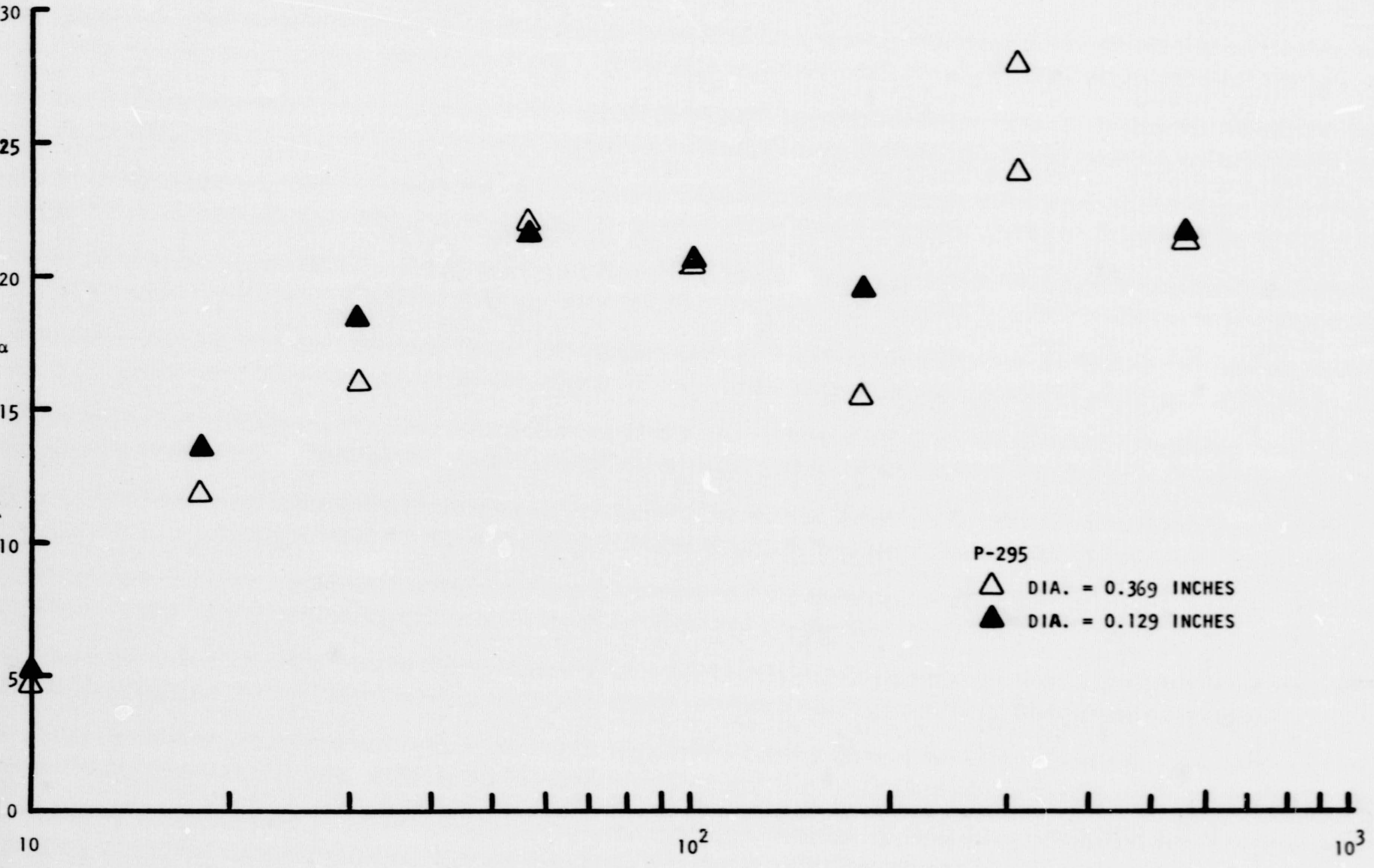

FIGURE 1 α for P-295 additive at various concentrations and in two pipe sizes.

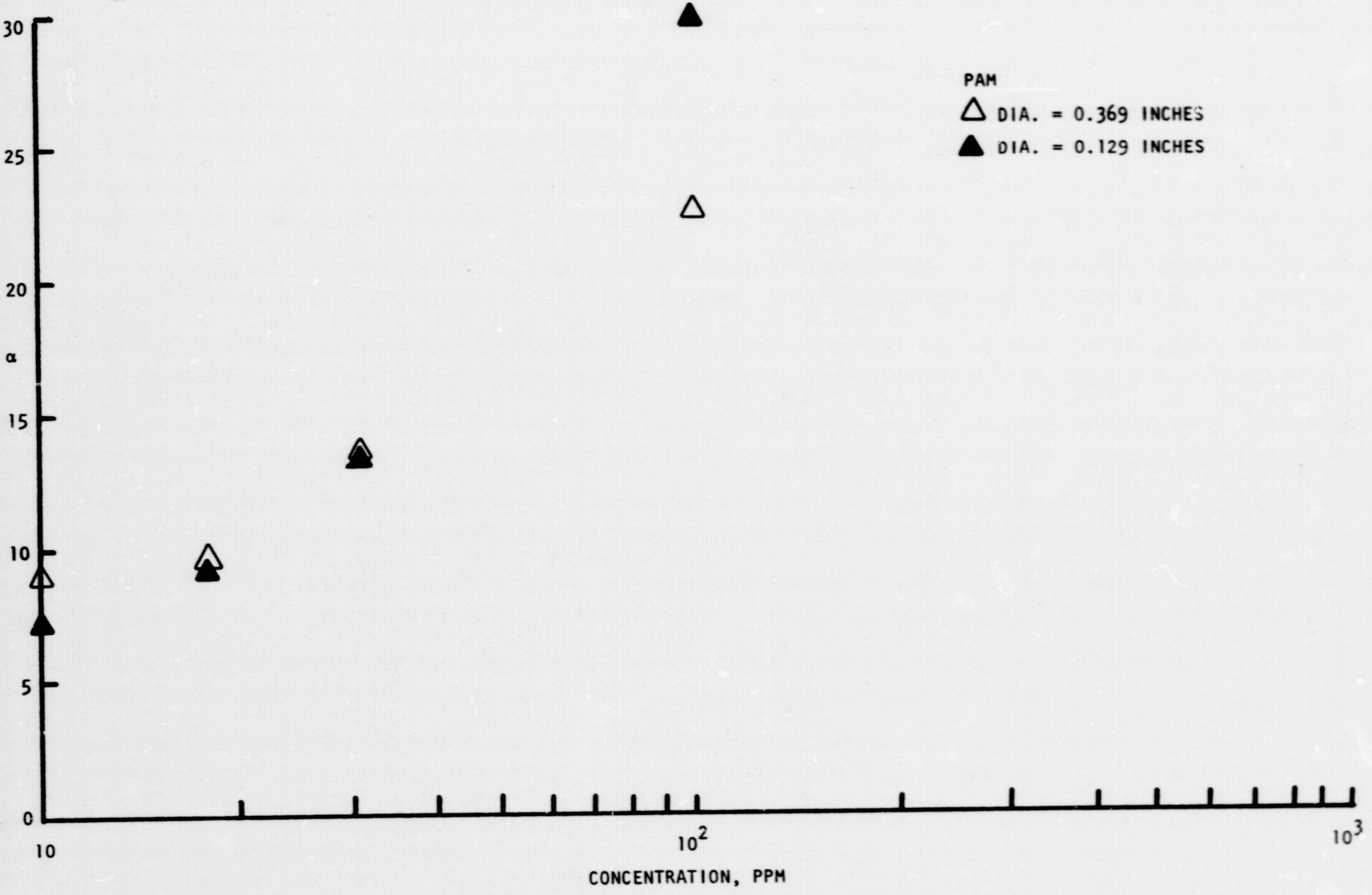

FIGURE 2 α for polyacrylamide additive at various concentrations and in two pipe sizes.

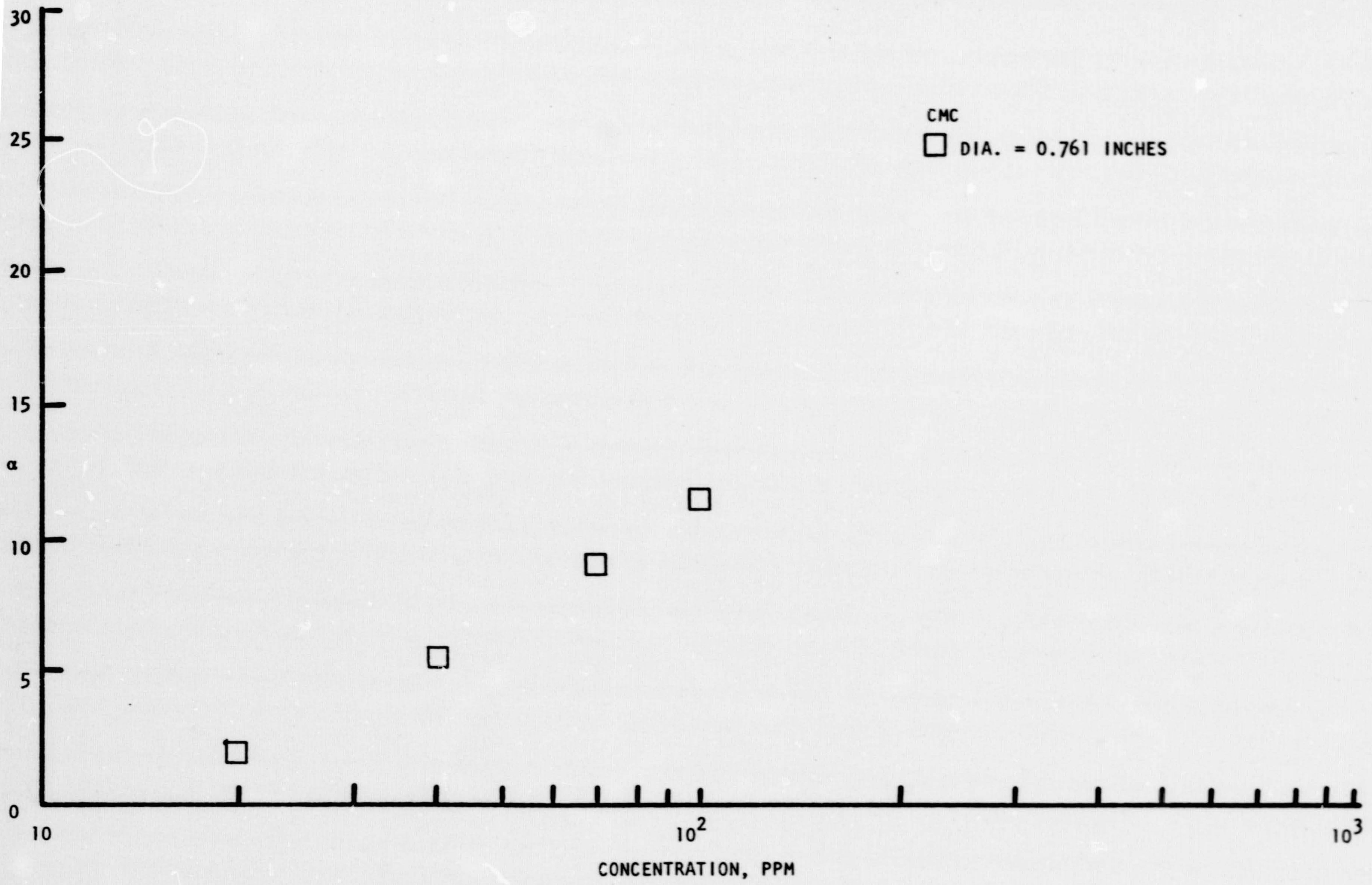

FIGURE 3 α for CMC additive at various concentrations in a 0.761-inch diameter pipe.

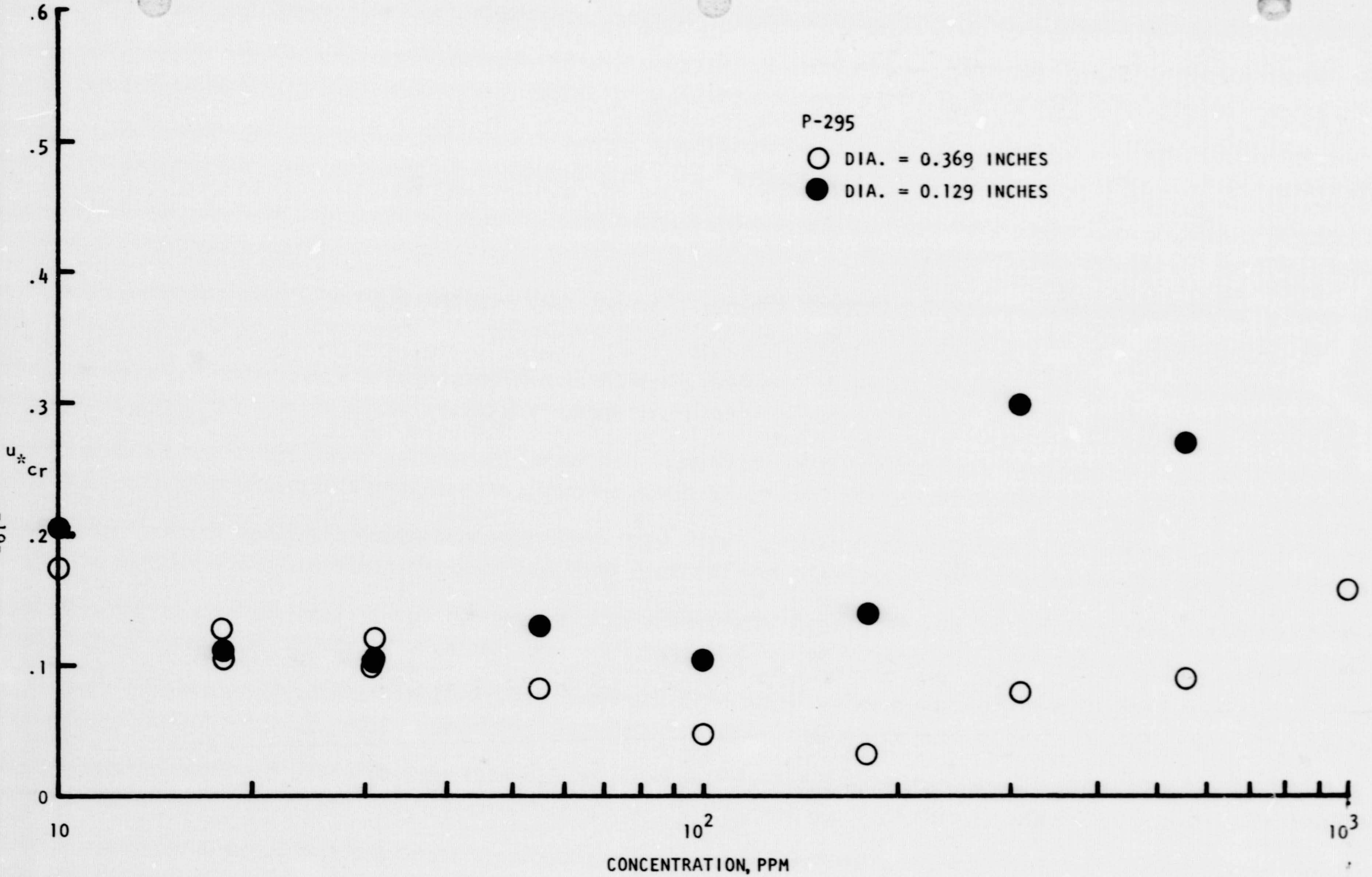

FIGURE 4 u_{*cr} for P-295 additive at various concentrations and in two pipe sizes.

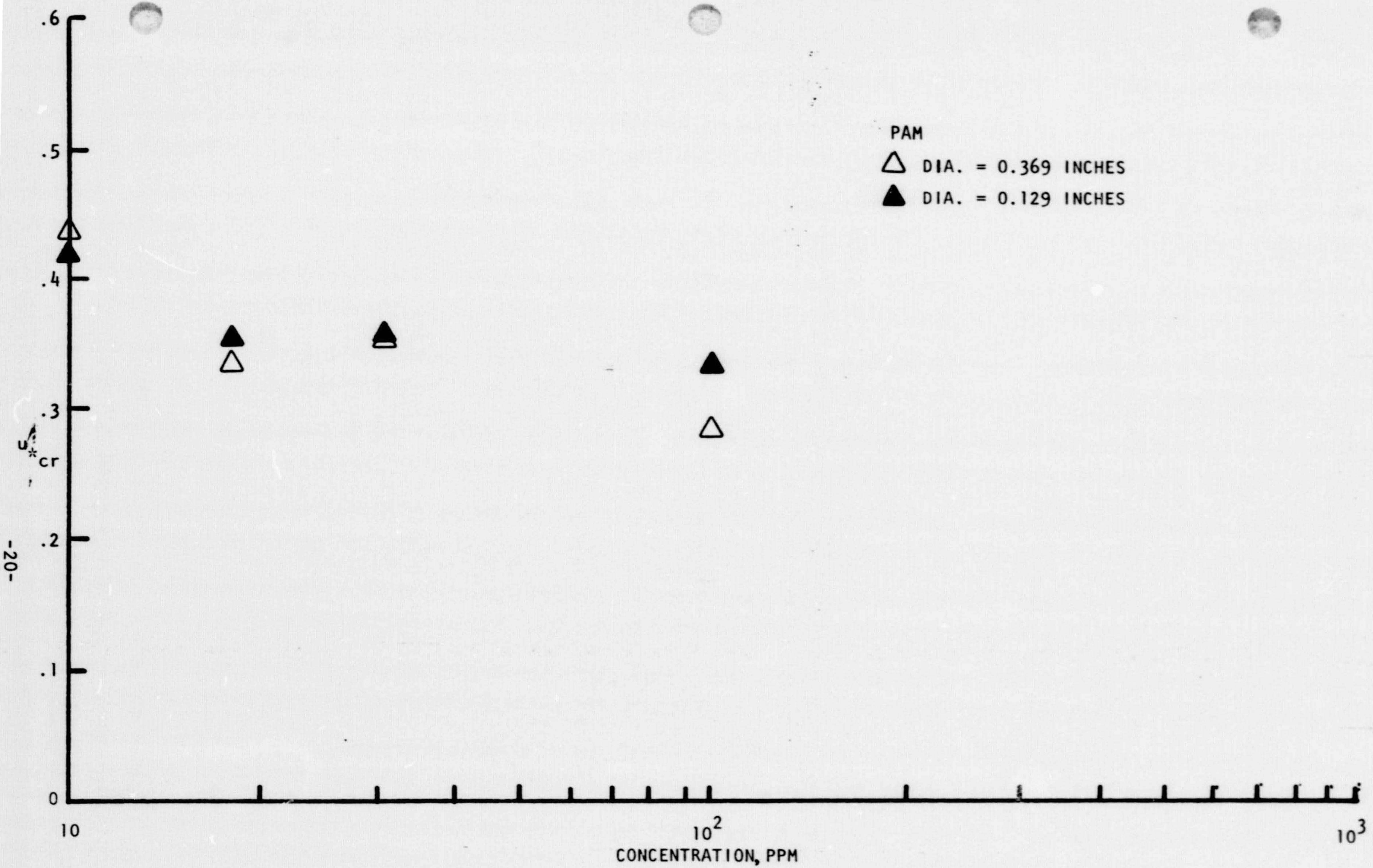

FIGURE 5 $u_{*_{cr}}$ for polyacrylamide additive at various concentration and in two pipe sizes.

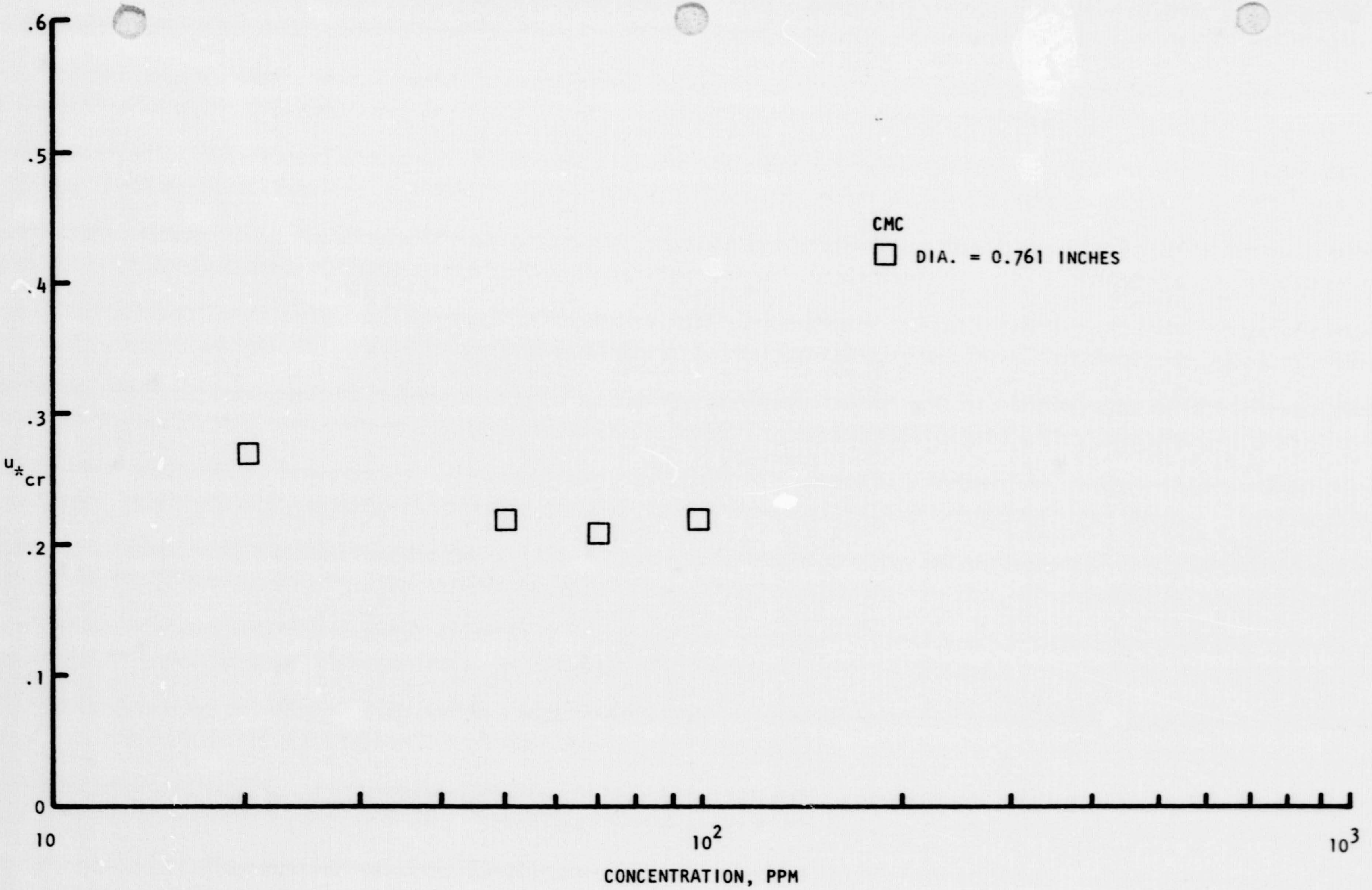

FIGURE 6 u_{*cr} for CMC additive in a 0.761-inch diameter pipe.