

IN DEFENCE OF NIKURADSE

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ABSTRACT

Nikuradse's (1932, 1933) classic smooth and rough tube data are currently regarded as invalid because of a number of unexplained changes he made to the data. Re-examination of his raw data suggests a previously unrecognised zero error on his wall distances. Allowance for this revalidates much of his data and suggests his data modifications were for more honourable reasons than often assumed. A previously unrecognised effect of roughness on Karman coefficient is revealed.

INTRODUCTION

In the late 1920's and early 1930's, Nikuradse was a highly prolific fluid mechanics experimentalist and analyst. His work provided a basis for early major advances. However, various authors (Miller 1949, Ross 1953, Robertson 1957, Robertson et al 1965, 1968, Lindgren and Chao 1969, among others) have criticised several aspects of his major works on smooth and artificially rough pipes (Nikuradse 1932, 1933). They suggest Nikuradse altered some of his experimental data to force apparent agreement with theoretical expectations. This casts doubt on all his data. However, his data, if valid, is still useful as it covers flow conditions not since experimentally re-examined.

EXAMINATION OF QUESTIONED ASPECTS OF NIKURADSE'S WORK

Nikuradse's (1932) wall distance shift for smooth tube velocity profiles

As first reported by Miller (1949) and widely noted since, when Nikuradse (1932) non-dimensionalised his raw smooth pipe velocity profile data, he added, without explanation, 7 to his y^+ values. The unadjusted data apparently supported validity of the log-layer down to $y^+=3$. The adjustment was insignificant except for low y^+ data. These were all obtained for his smallest bore tube. Miller (1949) stated that Nikuradse (1932) invalidly made the adjustment to force agreement with Prandtl's laminar sublayer hypothesis.

However, Miller (1949) did not base this view on a belated justification he obtained from Nikuradse, as is often supposed (eg Lindgren and Chao 1969). It is instead Miller's reinterpretation of Nikuradse's belated explanation that the adjustment avoided an apparently lower near-wall total viscosity than that due to molecular processes alone. This justification is reasonable. Moreover, the non-adjusted data does not exclude the possibility of a laminar sublayer, as supposed by the conventional interpretation of Nikuradse's adjustment, but instead limits its extent to lower wall distances ($y^+ < 0.1$). Also, other data have since confirmed Nikuradse's adjusted data. Interestingly, and not widely known, is that Nikuradse's (1932) analysis omitted data from his two nearest-wall locations, even though these add support to the trends of his adjusted data, perhaps because of difficulty in allowing for wall effects on his pitot readings, extensively discussed in his 1932 paper.

The present work re-examined Nikuradse's (1932) raw velocity data, including those omitted from his own analysis. In all cases, a shift compatible with a wall location zero error produced agreement with the "universal" profile (that of Beattie 1992 was used) and/or experimental profiles from the literature obtained at identical dimensionless conditions. The inferred zero errors were insignificant except for his smallest bore tube, for which they closely correspond to Nikuradse's chosen shift. Perhaps his "zero" location aimed to position the pitot edge at the wall for this tube, and to position the pitot centre at the wall for the other tubes. For his smallest tube, the inferred actual location of his " $y=0$ " data was sufficiently far from the wall for wall effects to be negligible.

Figs 1 and 2 show the re-evaluated data for the smallest tube. These figures validate his raw data if a zero wall location error is acknowledged. His wall distance shift closely corresponds to the inferred zero errors for the smallest tube. Fig 1 reveals a previously unreported and invalid downward velocity adjustment, by a factor 1.50, in Nikuradse's (1932) processed $Re=4040$ data, presumably to force compatibility with his other data. A similar shift is evident in Nikuradse's (1930) $Re=3000$ data.

Various authors imply a sinister motive when noting an absence of explanation for his wall distance shift. Such implied motive is inconsistent with his report including raw data from which the shift may be uncovered. A more charitable interpretation of no explanation is sloppiness arising from high productivity. The shifted zero location for different tubes inferred from this work demonstrates sloppiness. Another example of sloppiness is Nikuradse's (1932) above-noted extensive discussion of near-wall effects even though he omitted his perceived near-wall results from his nondimensionalised data.

Anomalous smooth tube pipe factor data

For a flow with fanning friction factor f and logarithmic velocity profile with Karman coefficient κ , the pipe factor P (ie average/maximum velocity $\langle u \rangle / u_{\max}$) is given by

$$P = \{1 + 1.5(f/2)^{-5} \kappa^{-1}\}^{-1} \quad (1)$$

Nikuradse (1932) omitted pipe factors from his 16 tabulated velocity profiles. His tabulated pipe factor data, presented later in his report, agree with pipe factors from other experimentalists. They deviate slightly from equation (1), particularly at lower Re , because this equation does not allow for the wake region of the velocity profile.

Ross (1953) obtained pipe factors from Nikuradse's (1932) velocity profile data. These agreed with Nikuradse's (1932) tabulated pipe factors except for data from his smallest tube. For this tube, pipe factors obtained from profiles were higher than tabulated pipe factors at nominally identical conditions. They also agree with equation (1) for the Karman coefficient value considered valid by Nikuradse (0.4). Ross suggesting that, to obtain this result, Nikuradse altered the pitot tube readings he obtained for his smallest tube. Figs 1 and 2 suggest otherwise.

The above-noted wall zero error offers a more charitable interpretation of the pipe factor discrepancies. The neglect of these errors would cause discrepancies between average velocity from integration of the pre-shifted profiles and his known flowrates. For consistency with the centreline pitot tube readings, Nikuradse perhaps chose average velocities obtained from his pre-adjusted profiles. In line with this interpretation, the anomalies disappear when his flowrates are corrected by the ratio of flowrates obtained by integrating adjusted and unadjusted velocity profiles.

The inferred understandable but invalidly adjusted average velocities in Nikuradse's "raw" velocity profile data have not been allowed for in figs 1 and 2. Effects are small, and only noticeable for the two lowest Reynolds numbers. If allowed for, compatibility with other data increases slightly.

Incompatible pipe factors for smooth and hydraulically smooth rough tubes

Robertson (1957) raised similar doubts about Nikuradse's (1933) pipe factor data for artificially rough tubes. He noted that the pipe factors for hydraulically smooth conditions (ie friction unaffected by the roughness) disagree with those for smooth tubes at the same Reynolds numbers. They instead agree with equation (1) with Karman coefficient 0.4 considered valid by Nikuradse. Robertson et al (1965, 1968) suggest Nikuradse (1933) modified his pipe factor values to force this agreement.

However, examination of Nikuradse's (1933) velocity profiles validates his hydraulically smooth pipe factors. As with his smooth tube velocity profiles, his rough tube velocity profiles for hydraulically smooth flows, as obtained from his raw data, also agree with the "universal" profile if adjusted by an inferred zero error. This is of sufficient magnitude that even his " $y=0$ " data, which he neglected from his analysis, are outside the viscous sublayer (fig 3). However, fig 3 demonstrates a negligible wake compared with smooth tube profiles. Thus, unlike the case for smooth tubes, pipe factors for hydraulically smooth rough tubes are expected to agree with equation (1). Contrary to the suggestion of Robertson et al (1965, 1968), Nikuradse's (1933) pipe factor data for hydraulically smooth flows in his rough tubes can now be seen to be valid.

The inferred zero error for wall distance would cause errors in integrated profiles in only the lowest Re data. For these data, fractional errors in wall distance are significant for a larger wall distance. Consistent with this expectation, Robertson (1957) noted discrepancies between integrated velocity profiles and actual flowrates in only four of Nikuradse's (1933) 41 profiles.

Anomalous rough tube pipe factor data

Robertson (1957) also raised doubts about the validity of Nikuradse's (1933) pipe factor data for hydraulically rough conditions. He found that Nikuradse's (1933) tabulated pipe factors for "fully rough" flows are larger than those obtained from his velocity profile tables at nominally identical conditions. Discrepancies increased with increasing roughness. Fig 5 presents data for the roughest tube. He noted that the scatter of the tabulated pipe factor data for rough pipes is much smaller than that of the pipe factors obtained from velocity profiles and that of pipe factors for Nikuradse's (1932) smooth tubes. Moreover, unlike the smooth tube pipe factors but like those for "hydraulically smooth" rough pipe flows, the tabulated "fully rough" pipe factors agree with equation (1) with the Karman coefficient value 0.4 considered valid by Nikuradse. Robertson et al (1965, 1968) suggest Nikuradse (1933) altered his tabulated pipe factors to force this agreement.

As with other aspects of Nikuradse's (1932, 1933) data, examination of "fully rough" velocity profiles obtained from his raw data provides insight to the validity or otherwise of Nikuradse's (1933) "fully rough" pipe factors. As with other velocity profiles considered above, profiles for "fully rough" agree with predicted trends and reduce data scatter if adjusted by an inferred zero error. The expected trend is a shifted logarithm profile. As with profiles considered above, the inferred error is of sufficient magnitude that even the " $y=0$ " data, which Nikuradse neglected in his analysis, is sufficiently far from the wall for any significant wall effects on pitot readings. Fig 4 shows representative data (those at the highest flowrate for each rough tube). As with profiles for hydraulically smooth conditions, fig 4 demonstrates a negligible wake compared with smooth tube profiles. In addition, the Karman coefficient 0.384 obtained for these data from the logarithm slope is lower than the 0.4 value considered valid by Nikuradse (1933) and others who later examined his work. The difference in smooth and "completely rough" Karman coefficients invalidates the widely used interpretation of Nikuradse's (1933) "completely rough" friction factors and velocity profiles in terms of a simple shift of the core region velocity profile.

Equation (1) with $\kappa=0.384$ is compatible with pipe factors obtained from velocity profiles (eg fig 5). This validates these pipe factors. Robertson's et al (1965, 1968) suggestion that Nikuradse (1933) made invalid "adjustments" to his tabulated pipe factors, shown above to be incorrect for "hydraulically smooth" data, appears justified for the fully rough data.

HUMAN FACTORS

The above indicates that Nikuradse did not adjust his data to the extent assumed, and, when he did, the adjustments were often for more honourable and valid reasons than often assumed. Nevertheless, some adjustments remain questionable. However, the literature contains many such data modifications without inviting the level of criticism directed at Nikuradse.

Often unrecognised human factors in science, such as faith in one's own theories, reduce objectivity but are necessary for scientific progress. These may explain both Nikuradse's scientific misdemeanours and the strong judgement of his detractors.

Nikuradse's data adjustments, questionable and otherwise, and those of other researchers, could be a result of a combination of time-pressure induced sloppiness; faith in theoretical expectations; a desire to see only that which conforms to expectations; and a desire to compensate for perceived experimental shortcomings. The present re-examination of Nikuradse's data suggests all these factors contributed to his data modifications.

The strong level of criticism directed to Nikuradse can be understood in terms of a tendency for people to reserve harshest judgement for their own unrecognised "faults" when seen in others. In this regard, publications critical of Nikuradse's work often contain the same "faults" the authors attribute to Nikuradse. Thus, for example, Lindgren and Chao (1969) criticise Nikuradse's origin shift but they acknowledge shifting their own near-wall velocity values- an equivalent shift- to conform to their theoretical expectations. Robertson et al (1965, 1968) also drew attention to Nikuradse's (1932) shifted origin at the wall. However, their archival 1968 paper does not indicate how they define their wall reference location for their rough wall velocity profile experiments. They give different definitions for their natural and artificial roughnesses in their less available 1965 report. Similarly, Miller's (1948) claim that Nikuradse (1933) misrepresented his data to satisfy what Nikuradse wanted to find is in fact a misrepresentation of Nikuradse's explanation of his wall origin shift to satisfy what Miller wanted to find. Seen in this light, these authors' judgements of Nikuradse can be seen as overstated.

CONCLUSIONS

The above re-examination of Nikuradse's data together with considerations on human factors affecting science suggest that Nikuradse's data manipulations are not sufficient to discredit his work to the extent sometimes considered. His data remain useful, but, as with other data, caution is needed when using them. The analysis uncovered a previously unrecognised data adjustment he made and a previously unrecognised modified Karman coefficient for his "fully rough" data.

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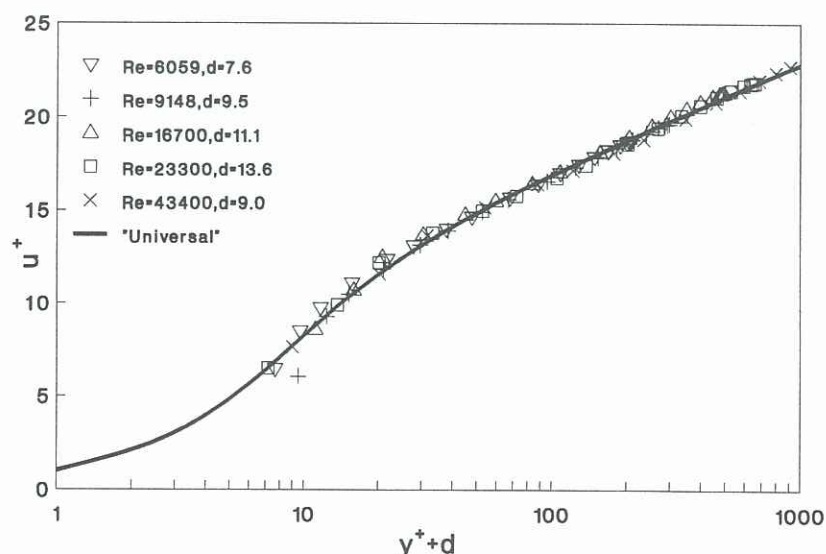


FIG 1. Agreement of "universal" profile and data obtained from Nikuradse's (1932) raw data, including " $y/r=0$ " and " 0.01 " data he neglected, and allowing for inferred zero error in y .

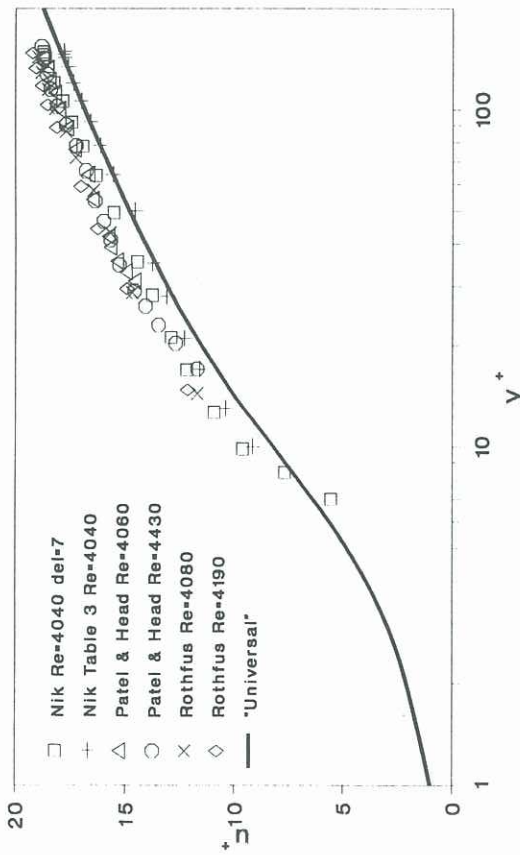


FIG 2. Comparison of "universal" profile; Nikuradse's (1932) $Re=4040$ velocity data from his raw results, including "y/r=0" and "0.01" data he neglected, allowing for inferred zero error in y (\square); his version of these data (+); and other published data at similar conditions.

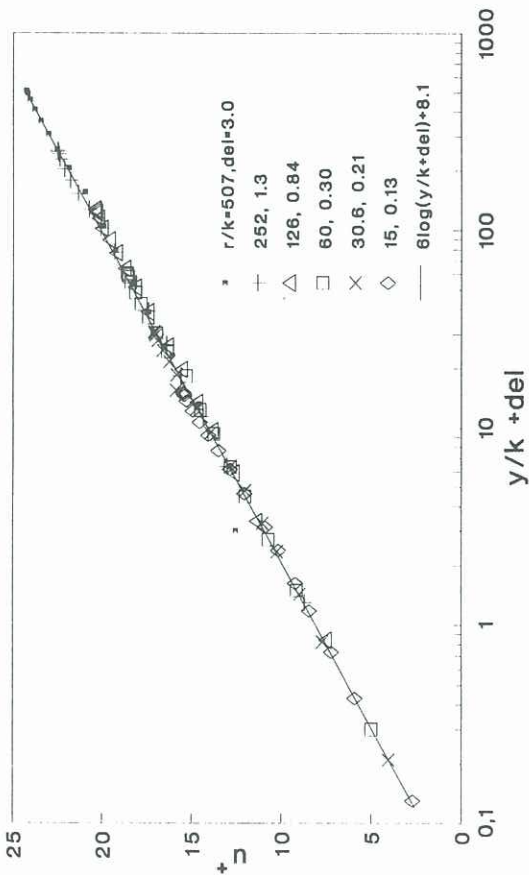


FIG 3. Agreement of "universal" profile and Nikuradse's (1933) hydraulically smooth rough pipe data, including "y=0" data he neglected, and allowing for inferred zero error in y.

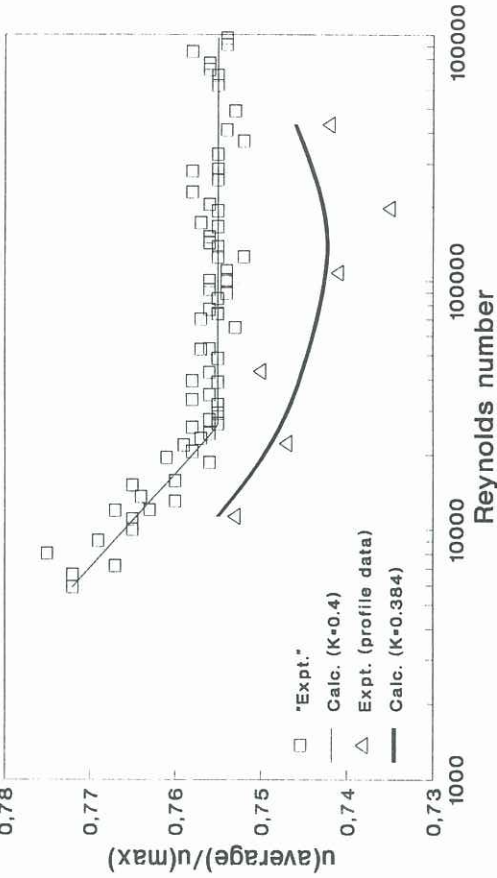


FIG 4. Shifted plot of Nikuradse's (1933) highest flowrate "completely rough" profiles, including "y=0" data he neglected, demonstrating a Karman coefficient of 0.384.

FIG 5. Comparison of Nikuradse's (1933) roughest tube pipe factors from tables (\square); from velocity profiles (Δ); predictions with $\kappa=0.4$ (assumed by Nikuradse); and with $\kappa=0.384$ (from Fig 4).