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The local enhancement of mass transfer at 180° bends

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Abstract—The effect that tight 180° bends have on locally enhancing the mass transfer, over the fully developed tube value, has been examined at Reynolds numbers up to 2.6×10^5. The initial or smooth enhancement has been shown to be less than 1.8: the final or rough enhancement was found to increase with Reynolds number—enhancement = $0.71Re^{0.12}$. This is consistent with mass transfer from a rough surface being dependent on the Reynolds number directly and not on the Reynolds number raised to a fractional power. Various possible mass transfer peaks were identified, particularly surprising were those 45° round the bend on its inside. The other position of mass transfer maxima at high Reynolds numbers was on the flanks between 90° and 180° around the bend. It has been established elsewhere that there is a relationship between the mass transfer coefficient and the rate of erosion corrosion of carbon steels in a power plant. The implications of the findings of the present work in predicting the occurrence of erosion corrosion are discussed.

INTRODUCTION

EROSION corrosion of carbon steels in pure water has occurred in a number of nuclear boilers [1]. This has been encountered in both single and two-phase regimes. The problem is invariably associated with regions of flow disturbance, e.g. downstream of orifices or ferrules, or at bends. There is ample evidence to support the idea that there is a relationship between the mass transfer coefficient (K) and the rate of erosion corrosion. Unfortunately, the rate of metal loss does not show the simple expected linear relationship on the product of ΔK and ΔC where C is the concentration driving force. Rather it appears [2, 3] that the corrosion rate depends on the mass transfer coefficient raised to a power between 1 and 3 depending on the pH and temperature, i.e. the rate of metal loss varies as: $K^n\Delta C$, where $1 < n < 3$. It has been suggested [2] that this unusual behaviour arises because the effective magnetite solubility increases with increasing corrosion rate.

It is important in making predictions [4] that both K and n are known accurately. The value of n can be determined by performing an erosion corrosion test on a specimen with a known mass transfer distribution—the region downstream of an orifice is well suited for this. Then, if the mass transfer of any other feature is known, it should prove possible to predict its erosion corrosion rate. Bends are the major geometric feature of boilers for which such predictions are needed.

Coney and co-workers [5, 6] have made an extensive review of both mass and heat transfer at bends; this was limited to the single phase situation, since no information was available concerning two-phase flow. The only available mass transfer work [7] utilized the sublimation of naphthalene in air ($Sc = 2.53$) at Reynolds numbers of 9×10^4 and 3.9×10^5 in a 90° bend with a ratio of bend diameter to tube diameter of 3. It was found that mass transfer was suppressed at the inside of the bend, but enhanced by about 70% at the outside and flanks of the bend.

There have been a number of heat transfer studies at bends which have produced conflicting results. In particular, in some heat transfer experiments involving heated bends [22, 23] enhancement factors as high as 4 were measured, whereas other heat transfer measurements suggested values below 2. Coney suggested that these discrepancies could be caused by irregular heating in electrically heated bends due to changes in wall thickness, and to density induced centrifuging, the effect of which would depend upon whether the bends were heated or cooled. Despite these problems Coney [5] tentatively suggested a correlation equation

$$\frac{Sh \text{ outside of bend}}{Sh \text{ fully developed tube}} = 1+2.2\left(\frac{r}{R}\right)^{1.2}\left(\frac{L}{d}\right)^{0.75}$$

where R is the average bend radius, r the tube inside radius, and d its internal diameter. L is the length along the centre line of the curved section of pipe, L/d has a maximum value of 30, R/r has a minimum value of 4 and the enhancement has a maximum value of 1.7. This equation predicts that the enhancement is independent of Reynolds number.

However, it was clear that more work was needed to characterize mass transfer in bends. The work reported here was undertaken to examine single phase mass transfer in bends. Particular attention has been

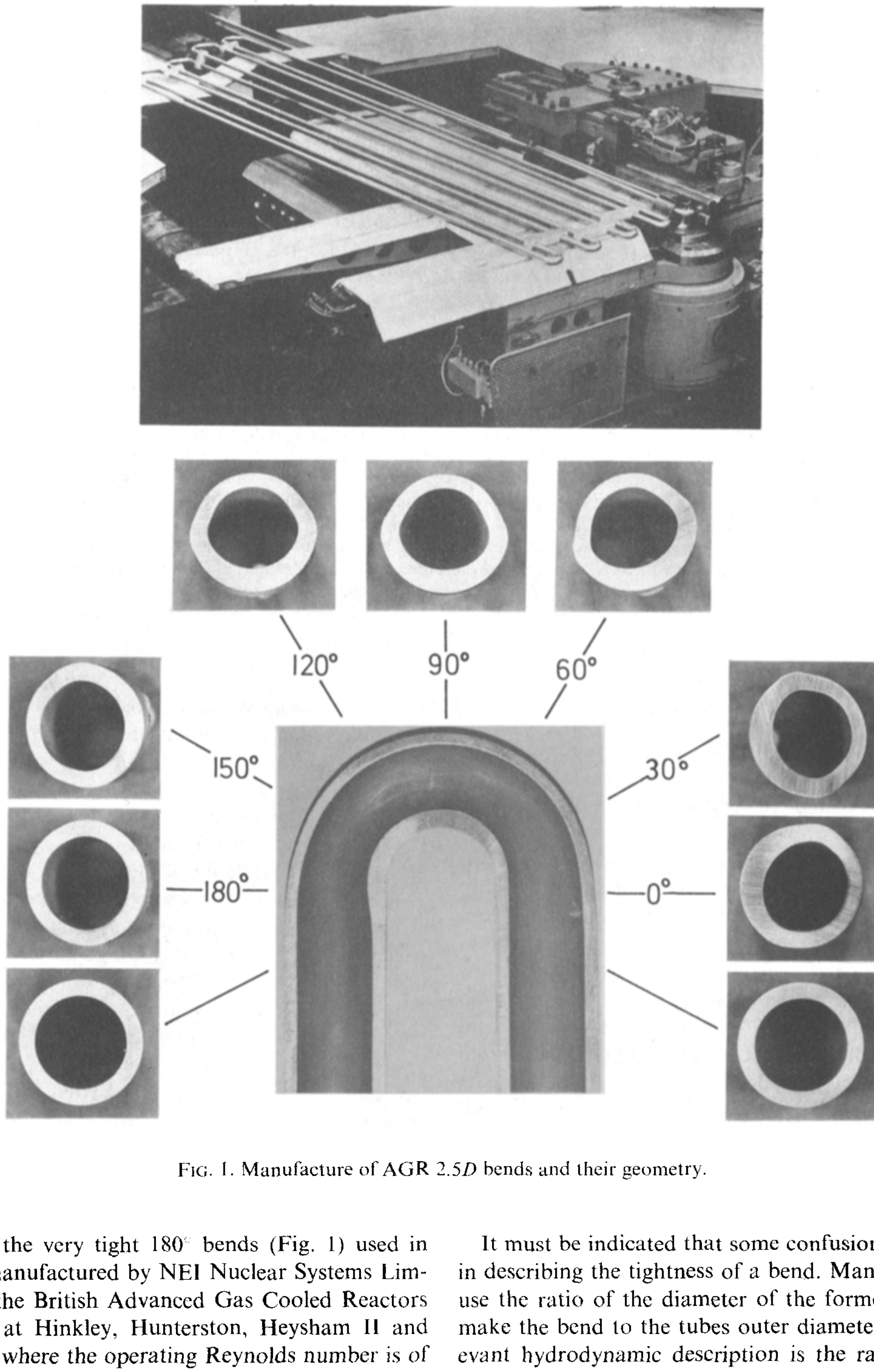

Fig. 1. Manufacture of AGR 2.5D bends and their geometry.

given to the very tight 180° bends (Fig. 1) used in boilers manufactured by NEI Nuclear Systems Limited for the British Advanced Gas Cooled Reactors (AGRs) at Hinkley, Hunterston, Heysham II and Torness, where the operating Reynolds number is of the order of 2×10^5. The technique used is the newly developed and tested method [4, 8] which relies on the corrosion of copper in acid ferric chloride solutions. The rate is controlled by the diffusion of ferric ions to the copper surface, where they are reduced to ferrous ions and the copper dissolves as a monovalent chloride complex. Parallel to this work, Wilkin and coworkers [6, 9] have been using the chemical dissolution of plaster of Paris in water, and Sprague *et al.* [10, 11] have been using the limiting current density technique (LCDT) to examine mass transfer at bends.

It must be indicated that some confusion can arise in describing the tightness of a bend. Manufacturers use the ratio of the diameter of the former used to make the bend to the tubes outer diameter. The relevant hydrodynamic description is the ratio of the average diameter of the bend to the inside diameter of the tube. The latter ratio is always the larger and is used throughout this report.

EXPERIMENTAL

Two kinds of bend were fabricated for the present experiments.

(1) A fully soft copper tube 15 mm o.d. with either a 0.7 or 1 mm thick wall was bent into 7.3D bends

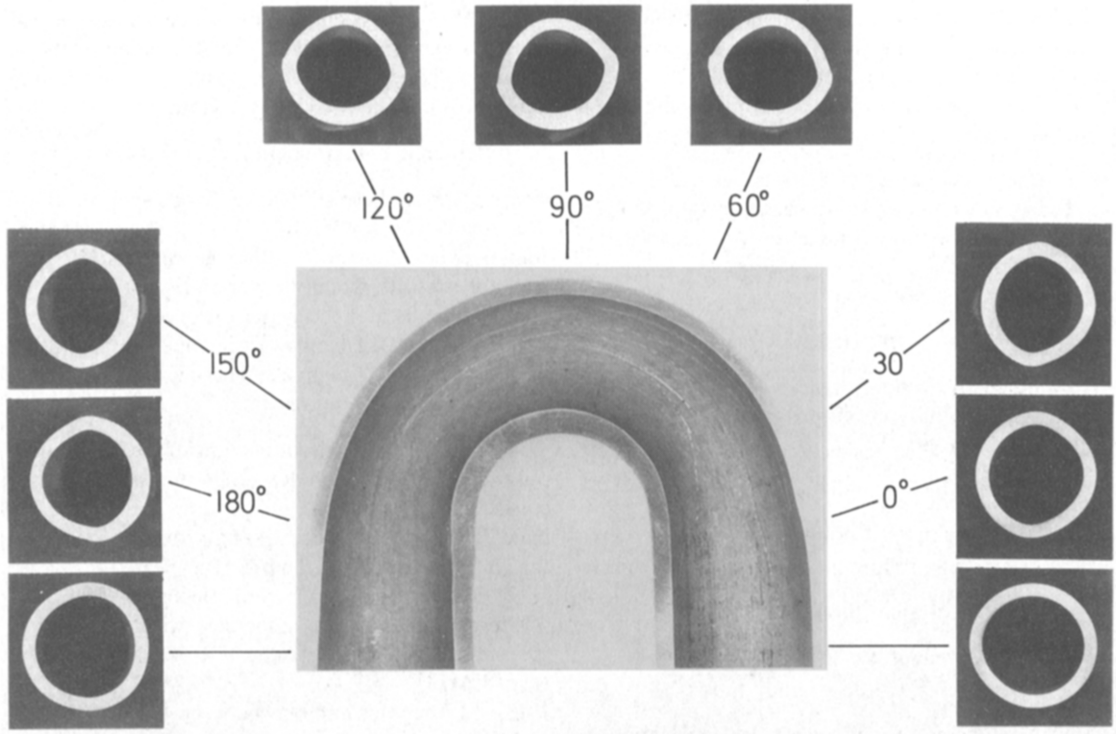

FIG. 2. Geometry of 2.5D test bends.

with a hand operated bender without the use of a spring.

(2) Half hard thicker walled (~2.7 mm) copper tubes 28 mm o.d. were stress relieved for 1 h at 450°C prior to being bent into 2.5D 180° bends using a production bender; in boiler maker terminology this is a 1D bend. Figure 2 shows the typical cross-sectional geometry of a 2.5D copper bend after bending. The similarity between this and the production bend (Fig. 1) is apparent.

It is clear that real bends are far from the uniform area circular cross-section ideal. However, it is difficult to quantitatively define a bend's geometry. The reduction in cross-sectional area, the degree of internal ellipticity and asymmetry, together with any sudden changes in cross-section, appear the most relevant properties. The reduction in cross-sectional area of the copper bend (28%) was greater than the production bend (20%) examined, whereas the ellipticity and asymmetry were very similar.

Analysis of the copper used indicated 99.95% purity with Zn the only detectable impurity. The solution used throughout this investigation was deoxygenated 0.1 N HCl containing 4 g l^{-1} ferric ions, added as ferric chloride. This was made up using deionized water and reagent grade chemicals.

The kinematic viscosity (γ) of the solution was taken to be that of water at 50°C (0.005534 $cm^{-2}\,s^{-1}$) and the diffusion coefficient (D) of ferric ions has been estimated to be 0.975×10^{-5} $cm^{-2}\,s^{-1}$; this gives a Schmidt number $Sc = D/\gamma$ of 568.

Most tests were carried out in a hydrodynamic flow rig described in detail elsewhere [8, 12, 13]. Briefly, it comprises a 20 l PVDF tank thermostatically controlled to 50±0.25°C, a centrifugal pump and a bypass and test circuit including calibrated rotameters and thermometers. The highest Reynolds number tests on the 2.5D bends were carried out in a new much larger rig with a 130 l tank a 7.5 kW pump and an impinging jet cell with facilities for monitoring the corrosion rate ultrasonically and hence obtaining the ferric ion concentration. For both bends a straight length of tubing 50 tube diameters long preceded the test bend to minimize the flow disturbance from previous bends in the rig.

The tube bore surfaces were degreased and the 28 mm tube bends were cleaned using concentrated HCl; the bend was then measured and weighed. Tests were carried out at fixed flow rates until failure occurred, a conductivity switch in a container beneath the bend terminating the test. The diameter of the specimen increased as dissolution proceeded and since the flow rate was maintained constant this resulted in the Reynolds number increasing with time. A bend with an enhancement factor of 2 would cause the Reynolds number in the straight section to decrease by about 10% just prior to failure. The test solution was replenished at suitable intervals to avoid depletion of ferric ions or a build up of copper in the solution.

Corrosion rates were derived in a variety of ways.

(1) Measuring the weight loss of a section of tubing, after any inlet effects, but preceding any bend effects. This gave an average fully developed tube flow value.

(2) Metallographically determining the thickness and the extent of roughening.

(3) Ultrasonic measurements using a Panasonic model 5223 wall thickness gauge with a resolution of 1 μm.

The last two techniques give local corrosion rates, the ultrasonic technique being particularly useful for measurements round the bend and for monitoring the progress of a test.

RESULTS

How much the bend enhanced the mass transfer compared to the fully developed straight tube value was obtained as follows:

corrosion rate at bend (μm h^{-1})

$$= \frac{\text{tube thickness at point of failure } (\mu\text{m})}{\text{failure time (h)}}$$

corrosion rate of straight tube (μm h^{-1})

$$= \frac{\text{weight loss (g)} \times 10\,000}{\text{area } (\text{cm}^2) \times 8.96 \times \text{failure time (h)}}$$

where 8.96 is the density of copper. By definition

enhancement factor

$$= \frac{\text{corrosion rate at bend}}{\text{corrosion rate of straight tube}}.$$

Substituting and eliminating this reduces to

enhancement factor

$$= \frac{\text{thickness at point of failure } (\mu\text{m})}{\text{wt. loss/cm}^2 \times 1116}.$$

This enhancement factor is an average value over the test period. For the thicker walled tubes, the tube is rough for most of the test, so the measurements provide an estimate of the rough enhancement factor.

Some initial experiments were performed on thin walled 7.3D 180° bends. Because of the thinness of these bends, it was felt that the results obtained should be most closely comparable with previous work on smooth bends. In Fig. 3 the obtained enhancement factors are plotted against Reynolds number with the failure positions shown. Also shown is the correlation suggested by Coney [5] and the LCDT results of Sprague [11]. The failures that occurred near the exit of the bend were associated with a slight expansion in the tube resulting from the bending process.

The mass transfer enhancement of the 2.5D 180° bends was examined at Reynolds numbers between 10^3 and 3×10^5. Attempts to measure enhancement factors as a function of time during the test were made using ultrasonic measurements. These were fraught with difficulties, particularly reproducibly positioning the probe in the region of highest mass transfer. Where measurements were made successfully during the early stages of a test, enhancement factors were 1.6 or less. The final or rough enhancement factors are plotted against Reynolds number in Fig. 4, together with the various failure locations, i.e. positions of maximum mass transfer. The correlation equation obtained was

$$\text{rough bend enhancement factor} = 0.71\,Re^{0.12}.$$

The scatter of the results around this line, resulting in a correlation coefficient of 0.74, was greater than similar experiments with other geometries [8]. This probably results from the variability of nominally identical bends and the variation in failure location. After each test the bend was cut open to reveal the pattern of surface roughness. These visual inspections indicated the following results.

(1) Extensive overall roughening of the bend region only developed at high Reynolds numbers and was consistent with a double helical flow path round the bend (Fig. 5(a)). This roughening did not occur on the straight sections of the tube.

(2) Failures that occurred on the inside of the bend 45° into the bend were associated with a change in surface features possibly indicative of flow separation (Fig. 5(b)).

(3) At Reynolds numbers between 4000 and 10 000, there were symmetrical ridges commencing on the inside of the bend at 90° and finishing near the flanks at 180° (Fig. 5(b)).

(4) At the lowest Reynolds number, failure again occurred in the line of sight position at the entry, i.e. where the axis of the straight tube intersects the bend.

(5) Only one failure occurred on the inside of the bend beyond the exit (Fig. 5(c)) with an enhancement factor of 1.74 at a Reynolds number of 4000. At higher Reynolds number, peaks in mass transfer occurred on the flanks of the bend beyond the exit (Fig. 5(d)) but failures always occurred elsewhere first.

DISCUSSION

From the practical viewpoint, it is the initial or smooth value of the mass transfer rate at bends which is the hydrodynamic parameter which will determine if erosion corrosion will occur; if it does it will be the rough value of the mass transfer coefficient which will influence the maximum possible erosion corrosion rate.

For the 7.3D bends, since the final enhancement factor is never greater than 1.8 (if $Re > 10^4$) the initial or smooth value will be less than this; possibly as low as 1.4, which is the value measured at low Reynolds numbers. It would appear that because these bends were made in relatively thin copper, limited roughness could develop. The roughness that developed in the bend region, of about 80 μm peak to peak, possibly caused the enhancement factor to increase from 1.4 to about 1.8. However, the effect of roughness is probably less than this because failures were associated with the tube expansion at the exit. Figure 3 shows there is reasonable agreement with Coney's [5] pre-

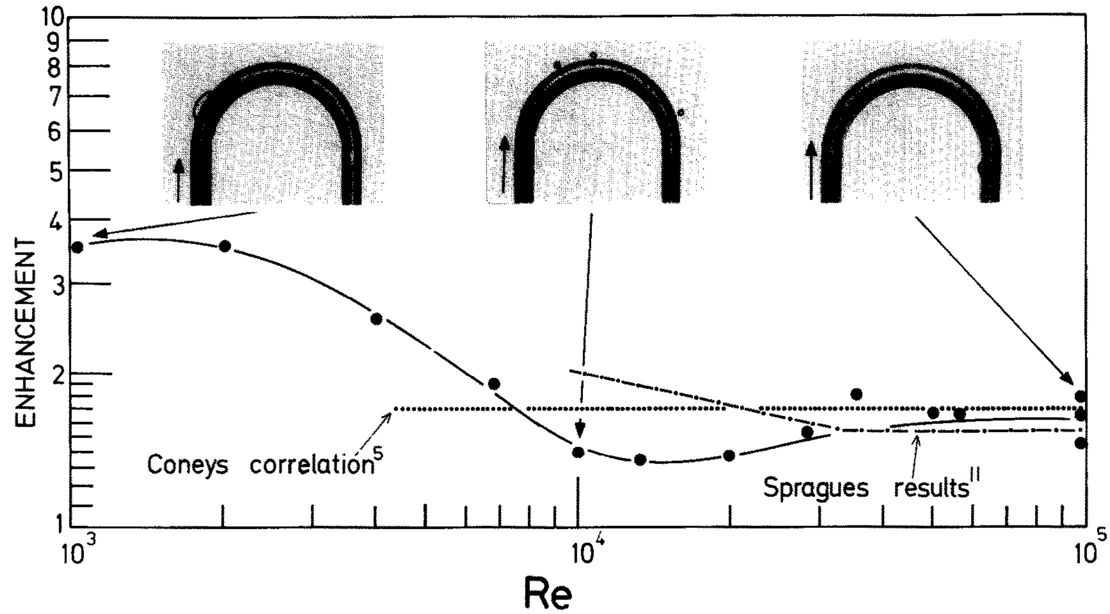

FIG. 3. Results for 7.2*D* copper bends plus LCDT results for 5.44*D* 180° bends and Coney's correlation.

dicted correlation and the recent LCDT results of Sprague [11].

With the 2.5*D* bends, it seems very probable that the initial or smooth enhancement factors are less than 1.8.

(a) Because values of 1.6 were measured during interrupted tests at $Re = 7\times10^4$ but it was difficult to measure the position of peak mass transfer.

(b) Because at low Reynolds numbers, enhancement factors of 1.7 were measured. There is no known basis (other than surface roughening) for this to increase with *Re*, in fact Sprague's results tend to show the opposite effect.

All this is in agreement with Achenbach's earlier work [7] on 3*D* 90° bends, which suggested a smooth enhancement factor of 1.7. It must be indicated that a 2.5*D* bend is, to our knowledge, the tightest bend used in boilers or other pipework systems. As such, it should represent the worst case and it is encouraging that the enhancement factor is not much higher than the 7.3*D* bend.

With the thicker walled 2.5*D* 180° bends, as dissolution proceeded the bend area preferentially roughened, showing up the flow lines and leading to enhancement factors of up to nearly 4. This surface roughening was very dependent on *Re* only occurring at high Reynolds numbers, in agreement with Coney *et al.*'s findings [6] for plaster bends. This appears to be the reason why enhancement factors at lower

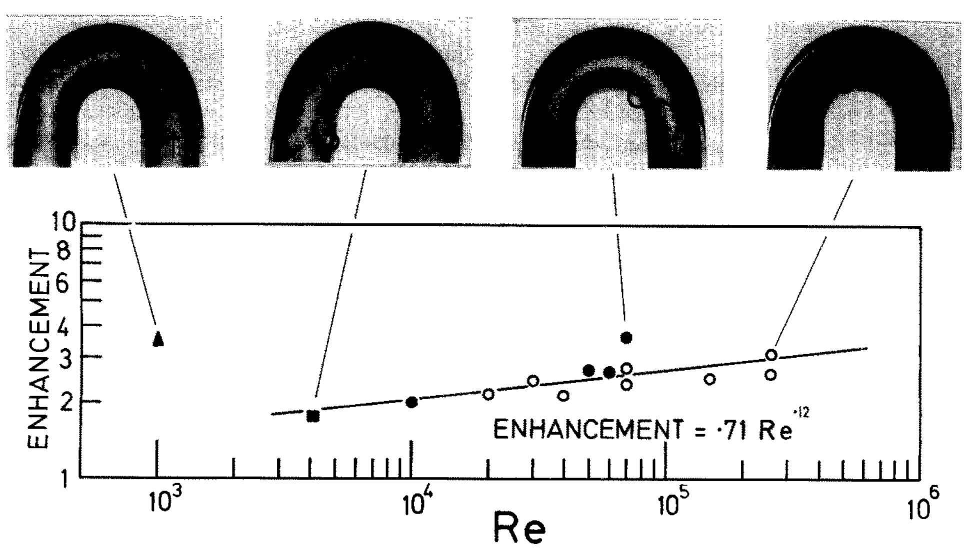

FIG. 4. Results for 2.5*D* copper bends.

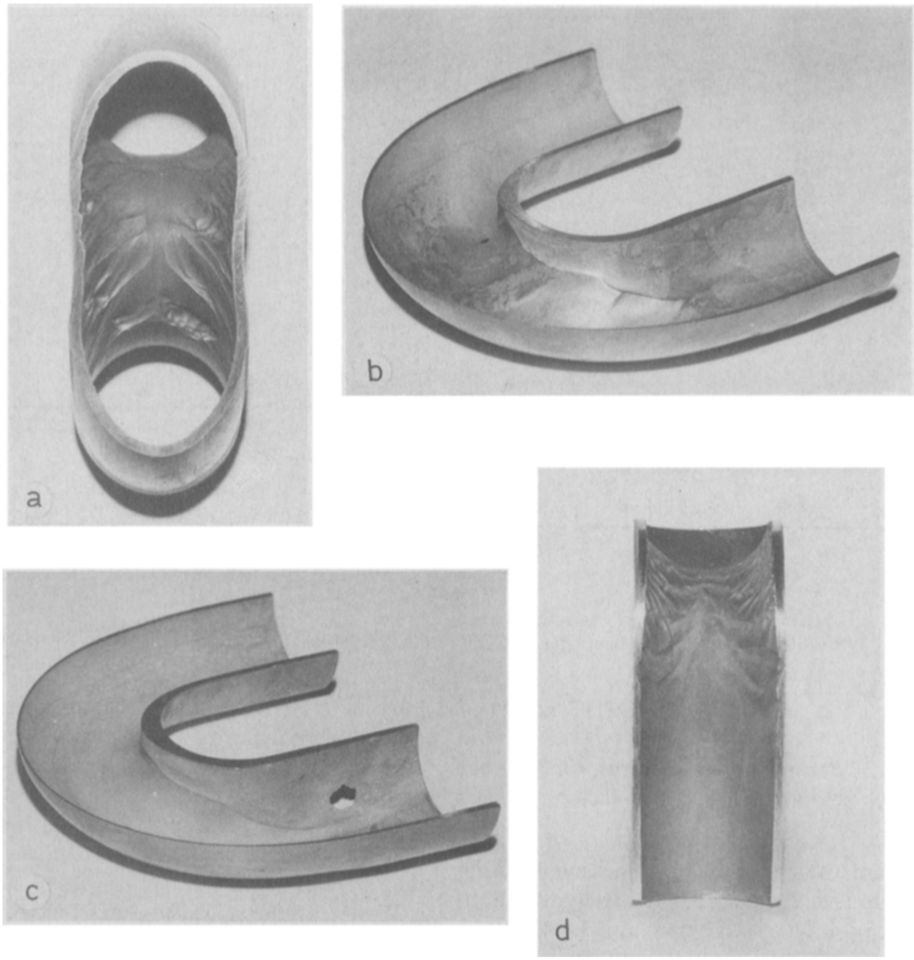

FIG. 5. Surface morphology of 2.5D bends: (a) symmetrical peaks at inlet to bend and general surface roughening at $Re = 70\,000$; (b) symmetrical ridge from 90° to 180° at $Re = 10\,000$; (c) failure at exit of bend on its inside at $Re = 4000$; (d) peaks in mass transfer on the flanks of the bend beyond the exit at $Re = 1.6 \times 10^5$.

Reynolds numbers were smaller, since, as discussed earlier, there is no evidence to suggest that smooth enhancement factors should increase with Reynolds numbers.

This is contrary to what simply might be expected, i.e. at high Re, flow is so turbulent that additional 'contributions' are not so important as at low Re. It is the effect expected if one considers that increasing the Reynolds number will produce a thinner concentration boundary layer. This is exactly the effect found by Kappesser *et al.* [15] using rotating cylinders of various initial roughnesses. This work convincingly showed that there was a critical Re value above which a given roughness enhanced mass transfer, that this critical value decreased with increasing roughness and finally that above the critical Reynolds number, the mass transfer rate was proportional to Re not $Re^{0.7}$.

An earlier classical paper by Dipprey and Sabersky [25] found very similar effects during heat transfer experiments on sand roughened surfaces. Additionally, they showed the importance of the Schmidt number in that the boundary layer thickness is thinner at higher Schmidt numbers and thus a smaller roughness height can disturb it. Because the Schmidt number in Dipprey and Sabersky's work was less than 6 it was thought less relevant than Kappesser *et al.*'s study where the Schmidt number was approximated.

Coney [5] using data of Blumberg and Curl [24] also suggested that mass transfer in a fully roughened tube was proportional to Re. In the present work this would suggest that the mass transfer rate from a roughened bend should depend on Re and not the $Re^{0.86}$ found for fully developed smooth tube flow. This would infer that the enhancement factor should be a function of $Re^{0.14}$. This is very close to our actual findings

$$\text{rough enhancement factor} = 0.71 Re^{0.12}.$$

Similar arguments can be applied to the roughness that develops downstream of an orifice or a ferrule.

If below a Reynolds number of 10^4 no roughness develops then the maximum enhancement factor for a smooth orifice or ferrule can be obtained by dividing the Tagg *et al.* [26] mass transfer correlation for a

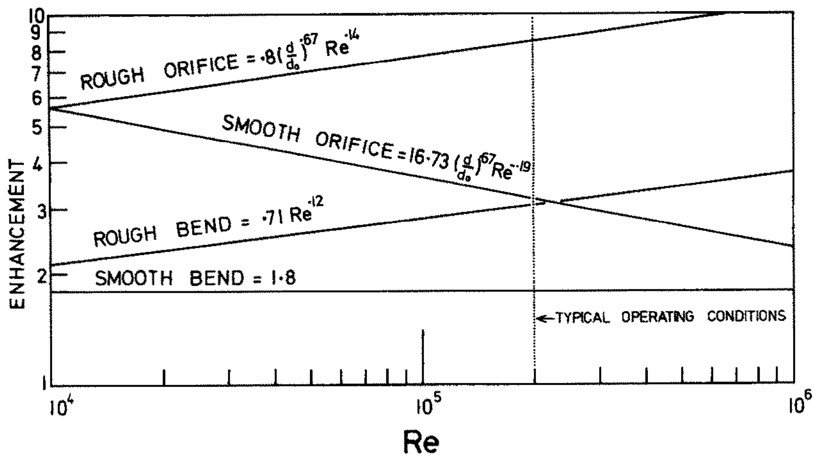

FIG. 6. Summary of enhancement factors at bends and orifices.

ferrule, or the Krall and Sparrow [27] heat transfer correlation for an orifice, by the Berger and Hau [28] correlation for fully developed tubular flow. After simplification this becomes [13]

enhancement factor smooth orifice

$$= 16.36\left(\frac{d}{d_0}\right)^{0.67} Re^{-0.19}.$$

Above a Reynolds number of 10^4 roughness develops downstream of the orifice with a Reynolds number dependency of unity; the Reynolds number dependency of the enhancement is obtained by dividing this by the Berger and Hau value for the fully developed tube flow of $Re^{0.86}$, i.e. $Re^{0.14}$. The constant relating the enhancement to the Reynolds number is obtained by assuming the rough and smooth enhancement factors are equal at a Reynolds number of 10^4, which gives

enhancement factor rough orifice

$$= 0.8\left(\frac{d}{d_0}\right)^{0.67} Re^{0.14}.$$

As shown in Fig. 6, this would have important effects on predictions. It is currently being examined, but earlier indications [8] were that isolated scallops formed rather than the general overall roughening observed in the region of the bends. These effects could also be important in tubing that is inherently rough. Rifled bore tubing might come into this category, in which case the enhancement in mass transfer would be $0.275Re^{0.14}$ but this does not allow for swirl effects.

It is clearly difficult to define when a surface is smooth, so that no mass transfer enhancement will occur, or when it is so rough further increases have no effect. Both these roughness values will depend on both the Reynolds and Schmidt numbers. The critical height (H_{crit}) of backward facing steps, above which mass transfer is enhanced, can be obtained from a value suggested by Coney [5]

$$H_{crit} = 60d\,Re^{-0.875}.$$

For the present tests at the highest Reynolds number (2.6×10^5) this would suggest that above a roughness height of 25 μm mass transfer would start being enhanced.

The enhancements obtained at higher Reynolds numbers are less than the values from plaster of Paris experiments on a less severe bend (5.4*D*). It is probable that this is due to some erosion [16, 17] occurring in the latter tests. In principal this can be examined by observing the effect of the concentration driving force; however, if attack is synergistic this might not be conclusive [18].

Both the 2.5*D* and 7.2*D* bends failed in a number of positions which varied with Reynolds number. Surprisingly, many of the 2.5*D* bends failed near the inside of the bend 50° into the bend. This is consistent with a double helical flow path round the bend [19, 20] producing a peak in mass transfer at $\pm 30°$ to the inside. However, the change in surface features near the failure, which possibly indicated flow separation, might well be important. This needs to be clarified by flow visualization studies.

Perhaps it is significant that Staddon [21] showed an increase in bend tightness caused a significant increase of heat transfer on the inside of the bend, although it remained lower than that measured on the outside of the bend and it occurred near the exit of the bend. There was no evidence of the 7.2*D* bends failing on the inside near the entry, so the tightness might be an important parameter which needs further mechanistic study. Other potential failure sites at bends include: the flanks between 90° and 180° or beyond; a region beyond the exit on the inner wall, probably associated with the expansion of the flow path and the fluid being thrown towards that wall by the bend, and finally, at very low flow rates, the so-called line of sight position at the entry.

CONCLUSIONS

(1) The mass transfer enhancement at 7.2*D* 180° thin walled bends was examined at Reynolds numbers between 10^3 and 10^5 and found to be consistent with smooth surface data.

(2) The mass transfer enhancement at 2.5*D* 180° thick walled bends was examined at Reynolds numbers up to 3×10^5. The initial or smooth enhancement is less than 1.8: the final or rough value is a function of Reynolds number

$$\text{enhancement factor} = 0.71\,Re^{0.12}.$$

(3) Various positions of mass transfer maxima have been identified in the 2.5*D* 180° bends, particularly surprising were the symmetrical maxima on the inside near the entry to the bend. These were possibly the result of flow separation. The other position of mass transfer maxima at high Reynolds numbers was on the flanks between 90° and 180° around the bend.

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ACCROISSEMENT LOCAL DU TRANSFERT DE MASSE POUR DES COUDES A 180°

Résumé—L'effet des coudes à 180° sur l'accroissement local du transfert de masse, par rapport au cas établi rectiligne, est examiné à des nombres de Reynolds allant jusqu'à $2{,}6 \times 10^5$. L'accroissement initial pour la surface lisse est un peu inférieur à 1,8; l'accroissement final pour la surface rugueuse augmente avec le nombre de Reynolds et il est égal à $0{,}71 Re^{0{,}12}$. Ceci est cohérent avec le transfert de masse, à partir d'une surface rugueuse, dépendant directement du nombre de Reynolds et pas du nombre de Reynolds porté à une puissance fractionnaire. De nombreux pics de transfert de masse sont identifiés qui sont particulièrement surprenants, comme ceux à 45° autour du coude. Une autre position des maxima, aux grands nombres de Reynolds, se trouve sur les flancs entre 90° et 180° autour du coude. Il a été établi ailleurs qu'il y a une relation entre le coefficient de transfert massique et la vitesse d'érosion–corrosion des aciers au carbone dans les centrales thermiques. On discute les implications de ces observations pour la prédiction de l'apparition de l'érosion–corrosion.

ÖRTLICHE ERHÖHUNGEN DES STOFFÜBERGANGS IN 180°-BÖGEN

Zusammenfassung—Örtliche Erhöhungen des Stoffübergangs in starren 180°-Bögen gegenüber der ungestörten Rohrströmung werden für Reynolds-Zahlen bis zu $2{,}6 \cdot 10^5$ untersucht. Es wird gezeigt, daß die Erhöhung am Eintritt kleiner als 1,8 ist; am Austritt steigt die Erhöhung mit der Reynolds-Zahl gemäß $0{,}71 Re^{0{,}12}$ an. Dies entspricht dem Stoffübergang an einer rauhen Oberfläche, der jedoch direkt von der Reynolds-Zahl abhängt und nicht über eine Potenzfunktion. Verschiedene Stoffübergangsspitzen werden festgestellt. Besonders überraschend sind diejenigen bei 45° an der Bogeninnenseite. Die anderen Stoffübergangs-Maxima bei hohen Reynolds-Zahlen liegen an den Flanken bei 90° und 180°. An anderer Stelle ist bereits nachgewiesen worden, daß es eine Beziehung zwischen dem Stoffübergangskoeffizienten und dem Fortschreiten der erosiven Korrosion kohlenstoffhaltiger Stähle in einem Kraftwerk gibt. Die Anwendung der Ergebnisse der vorliegenden Arbeit für die Voraussage des Vorkommens erosiver Korrosion wird diskutiert.

ЛОКАЛЬНАЯ ИНТЕНСИФИКАЦИЯ МАССОПЕРЕНОСА В ИЗОГНУТЫХ НА 180° КАНАЛАХ

Аннотация—В диапазоне чисел Рейнольдса до $2{,}6 \cdot 10^5$ исследовано влияние 180-градусных изгибов на локальное увеличение массообмена по отношению к характерной его величине для полностью развитого течения в трубе. Показано, что начальное или плавное увеличение не превышает 1,8 раза, а конечное или резкое увеличение возрастает с числом Рейнольдса как $0{,}71 Re^{0{,}12}$. Это сопоставимо с массопереносом от шероховатой поверхности, который, правда, зависит непосредственно от числа Рейнольдса, а не от числа Рейнольдса в дробной степени. Обнаружена возможность нескольких максимумов массопереноса; особенно неожиданными были максимумы в районе около 45° по ходу изгиба с внутренней его стороны. Другое положение максимумов массопереноса наблюдалось при высоких числах Рейнольдса между 90° и 180° по ходу изгиба на боковых по отношению к нему стенках. Установлено, что существует зависимость между коэффициентом массопереноса и интенсивностью эрозионной коррозии углеродистых сталей в энергетических установках. Обсуждается возможность применения результатов данного исследования при расчете возникновения эрозионной коррозии.