11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

PRESSURE LOSSES IN SINE-WAVED TUBE FLOW

C.O. POPIEL, J.H.C. HATTINGH, F. ROSSLEE and D.F. van der MERWE

Energy Laboratory, Rand Afrikaans University
PO Box 524, Johannesburg 2006, SOUTH AFRICA

Abstract: The results of measurements of pressure losses in a strongly curved, sine-waved, smooth tube, 20 mm diameter and having a centreline described by the formula $y=25\sin(2\pi x/100)$, are presented. Flow visualization with red and blue dye solutions injected at the entrance to the tube revealed that the flow separation (at the outer wall of the first bend) and flow disturbances (behind the second bend) started at about Re=400. The fully turbulent trend in the friction factor and Reynolds number relationship started at Re=3200. The friction factor obtained appeared to be much higher than given by existing data valid for higher ratios of the minimum radius of curvature to the tube diameter and for higher ratios of the wave amplitude to the tube diameter.

On leave from the Tech-University of Poznan, 60965 Poznan, Poland.

NOTATION

D - diameter of the tube
$F_w=\Delta P/(\frac{1}{2}U^2\rho L/D)$ - friction factor in wavy tube flow
F_s - friction factor in straight tube flow
h - wave amplitude (height)
n - number of waves
$R_c=\lambda^2/(2\pi)^2h$ - minimum radius of the sine wave curvature
$Re=UD/\nu$ - Reynolds number
U - main velocity
λ - wave length

INTRODUCTION

The sine-wave tube shape can become one of the most efficient tube shapes used in the heat exchangers because of the more vigorous mixing provided by the alternating bends than, for example, in coiled pipes (Shimizu et al., 1982) and because of the easy relaxation of possible thermal stresses. It will find more application when the fluid and heat flow characteristics for wavy tubes will become known and the optimization of the tube geometry will be possible. At present, the authors noticed the use of this type of tube in heat exchangers to warm up water in domestic heating systems. This tube configuration is also used in plate solar collectors.

Flow in a toroidally-curved pipe (in practice, helical coil) and in a single bend of circular cross-section is very well recognized (Ward-Smith, 1980; Berger & Talbot, 1983; Ito, 1987). The fluid near the pipe axis, having higher velocity, is subjected to a larger centrifugal force than the slower fluid at the pipe walls. The fluid moves outwards in the central region of the pipe and inwards near the wall. This leads to the creation of a secondary flow imposed on the main axial flow (seen as a contra-rotating helical vortex pair).

In a short bend a fully-developed curved flow cannot be attained. The flow in a single bend can be even more complicated, for example, in 90°-bend having a ratio of centerline curvature radius to the tube radius $2R_c/D<3.0$ separation and reversed flow occur. Therefore, the exact theoretical (Ward-Smith, 1980) or numerical solutions (Murata et al., 1976) are not easy. According to measurements of Ito (1960) the strong influence of the bend curvature on the pressure difference between outer and inner walls appears about two diameters upstream and exists about three diameters downstream from the bend. The velocity profile distorted by the bend will probably persist for about fifty or more diameters downstream from the bend. The above observations indicate the complexity of the flow approaching a consecutive bend (crest) in the wavy pipe. The pressure losses in wavy tube flow will be the result of a very complex velocity gradient distribution on the pipe wall.

In this communication the results of measurements of the pressure losses and flow visualization in a wavy tube are presented. A comparison of the friction factors obtained by various authors for different geometrical parameters shows the importance of the various parameters describing the shape of the centreline of the wavy tube.

EXPERIMENTAL SETUP

Pressure measurements and flow visualization were done using the same model of the sine-wave tube, which is shown in Fig. 1. The sine-wave tube of circular cross-section having 20 mm in diameter was manufactured with computer-controlled milling using a ball-nosed cutting-tool. A centreline groove of sinusoidal shape was milled in the two 20 mm thick transparent perspex plates representing two halves of the channel model. Tap water was used and flow rates were measured with a calibrated rotameter. Pressure losses

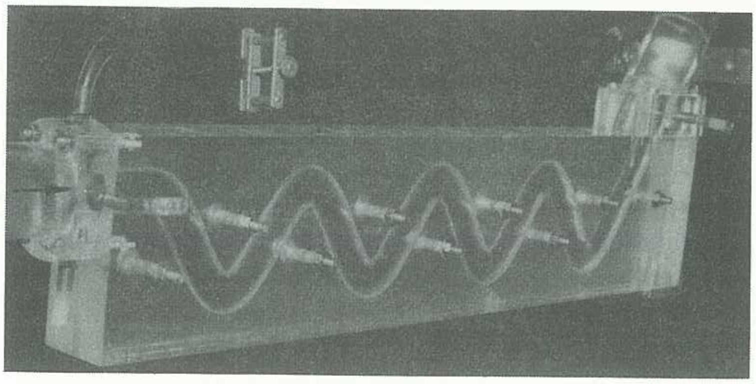


Fig. 1. Experimental model of the sine waved tube.

were measured with water U-tube and inclined manometers. For flow visualization a food colouring dye solution was used.

RESULTS AND DISCUSSION

Pressure losses.

In Fig. 2 the friction factors versus Reynolds number measured by various authors are shown. The differences between these results can be explained by different geometrical parameters of the periodically curved tubes, which are summarized in Table 1. The highest factor was obtained by the authors of this report due to a very low ratio of the minimum radius of tube curvature to the tube internal radius $(2R_c/D)=1.0$, which could be achieved by a special manufacturing technique. In this case a very strong secondary flow was induced. The purely laminar trend in the friction factor and Reynolds number relationship persists up to a Reynolds number of about $Re< \sim 400$ and the fully turbulent one sets in at a Reynolds number of about $Re> \sim 3200$. It was consistent with the direct observations obtained with the flow visualization. In the experiments of Popiel and Skupio (1987) the transition to the full turbulent trend is observed at about $Re> \sim 3500$. Their experiments were done with the heat exchanger stainless steel tube (6.8/8.0 mm in diameter) having the lowest curvature radius $(2R_c/D=2.94)$ which could be obtained for this tube. The results of Abou-Arab et al. (1991) are relatively close to the straight tube data. Their ratio of $(2R_c/D)$ was in the range 1.407 to 90.09 but the ratio of the wave amplitude to the tube diameter was constant and many times higher $(h/D=10.0)$ than in the previous experiments. Their suggested correlation for the friction factor for the alternating curved tubes has the form

$$F_w = axF_s + bx(D/2R_c)^{1/2} \tag{1}$$

where: $a=1.21$ and $b=0.03$ - for laminar flow,

$a=1$ and $b=0.005$ - for turbulent region,

and is valid only for one fixed parameter $(h/D=10)$, as is clearly demonstrated in Fig. 3. The constants a and b are different for laminar and turbulent flows, but will vary with the parameter (h/D). For determination of a univer-

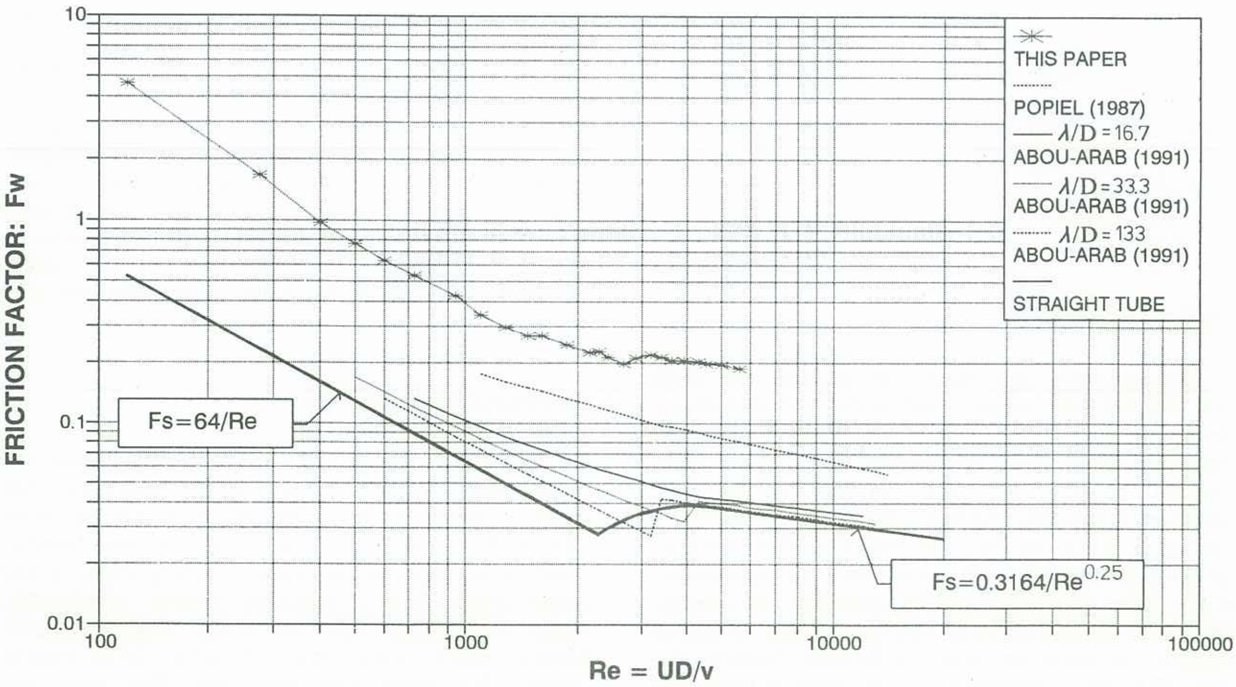


Fig. 2. Friction factor vs. Reynolds number for a sine-wave tube flow.

Table 1.

	D	n	λ	h	$D/2R_c$	λ/D	h/D
	mm		mm	mm			
This paper	20	3.75	100	25	1.013	5	1.25
POPIEL & SKUPIO (1987)	6.8	13	77	15	0.3396	11.3	2.21
ABOU-ARAB et al. (1991)	6	18	100	60	0.71	16.7	10
ABOU-ARAB et al. (1991)	6	14.5	200	60	0.1775	33.3	10
ABOU-ARAB et al. (1991)	6	10	400	60	0.0444	66.7	10
ABOU-ARAB et al. (1991)	6	5.5	800	60	0.0111	133	10
Straight tube			∞	0	∞	∞	0

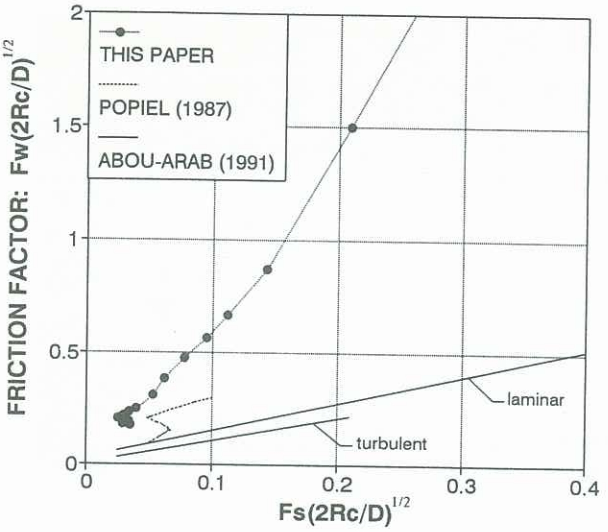


Fig. 3. Normalized friction factor for sine-wavy tubes.

sal correlation for the friction factor more comprehensive experiments are needed and are under way at the Rand Afrikaans University.

Flow visualization.

The red and blue dye solutions are injected into the flow 1.4D upstream from the first bend at the top and bottom or at the top and right side of the tube. At Reynolds numbers above about 400 the filament lines start to be slightly disturbed behind the second bend and a small separation zone is clearly observed at the outer wall of the first bend (Fig. 4a, c and d). At Reynolds numbers above about 1200 the chaotic movement of the filament lines is already observed behind the first bend (Fig. 4c and d). As the Reynolds number further rises the dye filament lines become invisible, being diffused by the fine scale turbulence. Comparing Fig. 4a and Fig. 4d having side injected dye solutions one can see that the secondary vortices are induced earlier at the lower Reynolds number.

The last two pictures in Fig. 4 (c and d) demonstrate that for very small ratio of the curvature radius to the tube diameter $R_c/D=0.5$ rather strong disturbances are observed, instead of a laminarization process, which takes places in a curved pipe flow at $Re_{cr}<2x10^4(D/R_c)^{0.32}$ for $R_c/D>10$ (Ward-Smith, 1980, p.269) or in laminar flow in a wavy tube, which takes place at $Re_{cr}<5012(D/2R_c)^{1/2}$ and is valid for $R_c/D>0.356$ at $h/D=10$ (Abou-Arab, 1991).

CONCLUDING REMARKS

1/ The effect of alternative curvature of the wavy tube on the friction factor is stronger in laminar than in turbulent flow particularly at higher ratios of the sine wave amplitude to tube diameter where the velocity profile promotes a stronger secondary flow.

2/ The laminarization effect of the curvature for the

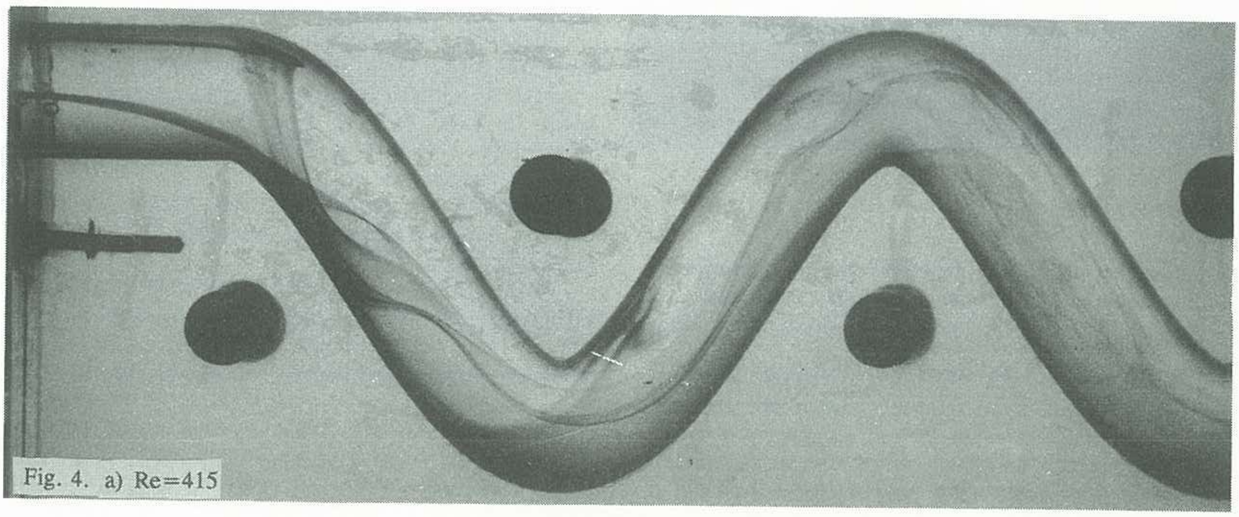
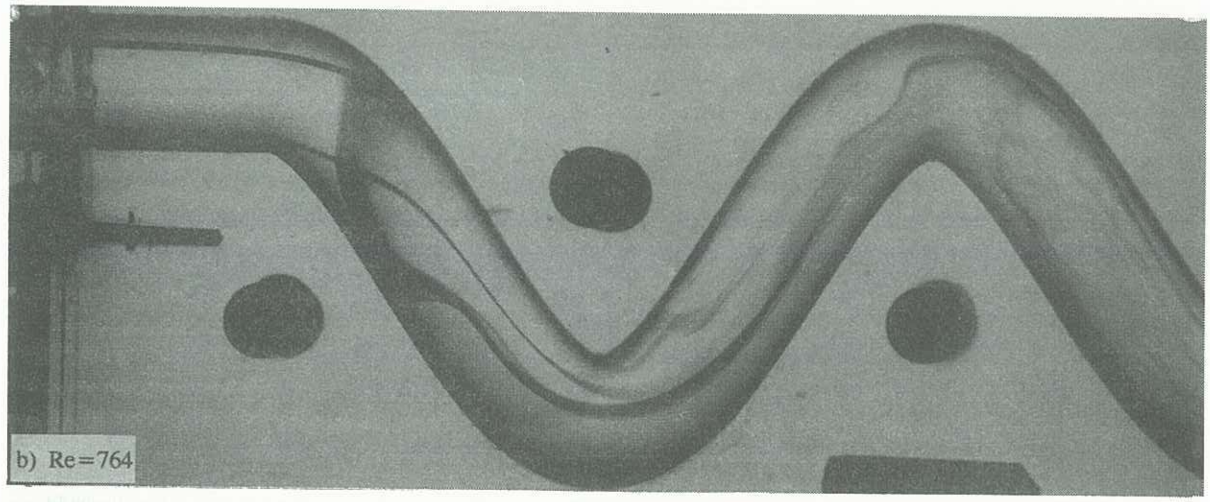
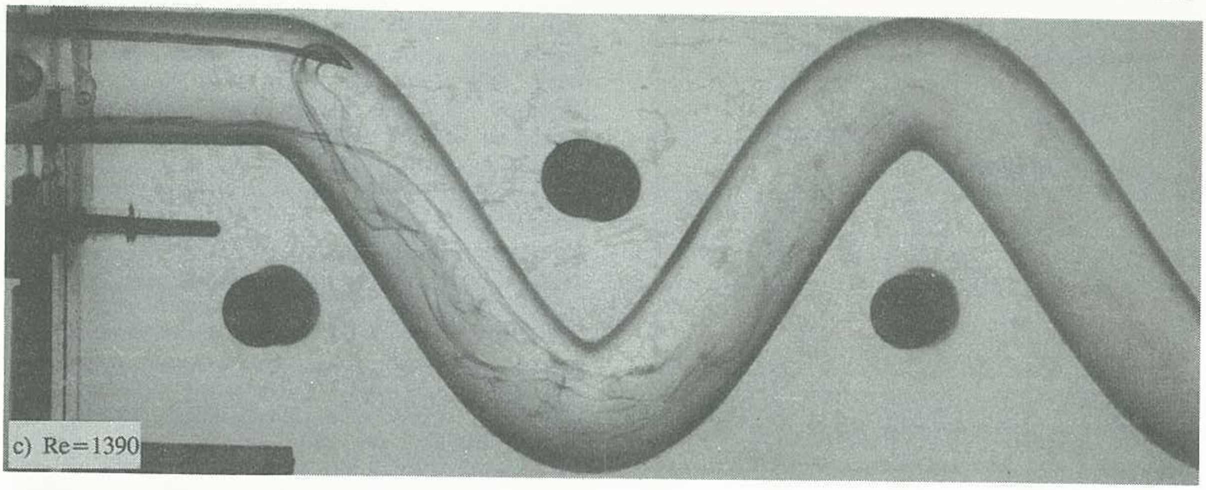


Fig. 4. a) Re=415





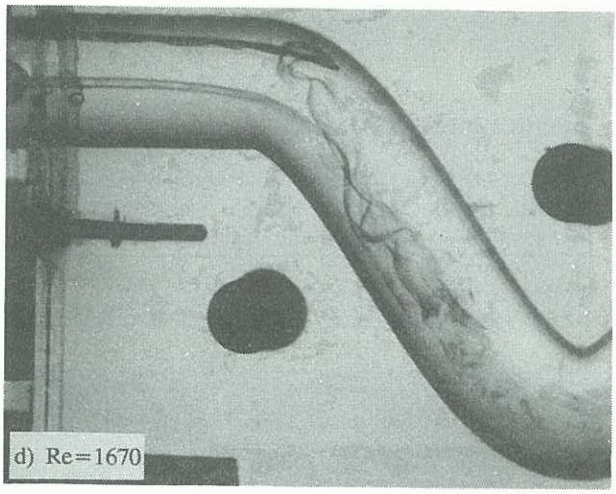


Fig. 4. Filament lines at the entrance to the sine-wavy tube:
a) Re=415, b) Re=764, c) Re=1390, d) Re=1670.

wavy tube that can be inferred from the measurements of Abou-Arab et al. (1991) at a higher amplitude to diameter ratio (h/D=10) was not observed in a tube having low ratio (h/D=1.25).

3/ The effect of the sine wave amplitude to tube diameter ratio cannot be ignored, particularly at small values of the ratio h/D<10.

4/ At present, a universal correlation for the friction factor in the sine waved tube flow is not yet available.

REFERENCES

ABOU-ARAB, T W, ALDOSS, T K and MANSOUR (1991) A Pressure drop in alternating curved tubes. Applied Scientific Research 48, 1-9.

BURGER, S A, TALBOT, L and YAO, L S (1983) Flow in curved pipes. Ann. Rev. Fluid Mech., 15, 461-512.

ITO, H (1960) Pressure losses in smooth pipe bends. J. Basic Eng. 82, 131-143.

ITO, H., (1987) Flow in curved pipes. Int. Journal J.S.M.E. 30, 543.

MURATA, S, MIYAKA, Y and INABA, T (1976) Laminar flow in a curved pipe with varying curvature. J. Fluid Mechanics 79, 735.

SHIMIZU, Y, SUGINO, K, KUZUHARA, S and MURAKAMI, M (1982), Hydraulic losses and flow patterns in bend pipes (Comparison of the results in wavy pipes and quasi-coiled ones). Bulletin of the JSME 25, 24-31.

WARD-SMITH, A J (1980) Internal Fluid Flow. The fluid dynamics of flow in pipes and ducts. Clarendon Press, Oxford.