Engineering Notes

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Turbulent Reynolds Analogy Factors for Nonplanar Surface Microgeometries

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Nomenclature

A	= model planform surface area
A_R/A_{FP}	= roughness-to-flat plate surface area ratio
C_f	= skin-friction coefficient
D	= drag
h	= roughness element height
h^+	= dimensionless height, $=(hU_\infty/\nu)(C_f/2)^{1/2}$
H	= convective heat-transfer coefficient
L_1, L_2	= wavy wall parameters
Q	= heat transfer
r	= oscillating transverse curvature parameter
Re_θ	= momentum thickness Reynolds number
s	= center-to-center roughness element spacing
s^+	= dimensionless spacing, $=(sU_\infty/\nu)(C_f/2)^{1/2}$
St	= Stanton number
T_w	= wall temperature
T_∞	= freestream temperature
U_∞	= freestream velocity
x	= streamwise distance
δ	= boundary-layer thickness
λ	= roughness element wavelength
ν	= kinematic viscosity

Introduction

CONVENTIONAL rough surfaces typically increase both drag and heat transfer. To quantify the relationship between heat transfer and drag for each surface, it is convenient to define a heat-transfer efficiency factor, proportional to the ratio between directly measured heat transfer and drag, which is exactly equivalent in form to the classical Reynolds analogy definition $St/C_f/2$. Reynolds analogy factors so constructed for conventional rough surfaces are typically below flat-plate levels, i.e., the required fluid pumping power increases more than heating rate for those surfaces.

By now it is well known that several nonplanar surfaces can reduce skin friction and, in some cases, produce net drag reduction.[1-6] Preliminary work conducted by Walsh and Weinstein[1] indicated that certain riblet surfaces seem to increase heat-transfer efficiency (Reynolds analogy factors up to 10% above reference flat-plate levels). In light of this work and the fact that numerous additional surface microgeometries are being developed in the NASA Langley Research Center Viscous Flow Branch as candidate drag reduction/turbulence control concepts, it is interesting to investigate the heat transfer associated with these nonplanar surfaces. This current study directly measures turbulent Reynolds analogy factors for 15 such nonplanar surface microgeometries (including riblets, oscillating transverse curvature, wavy walls, micro air bearings[4] in the Re_θ regime of 1638-2631. Surfaces producing Reynolds analogy increases are of value in optimizing the design of heat exchangers in terms of reduced size, cost, and weight.

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Test Apparatus and Measurement Procedures

Heat Transfer and drag measurements were obtained in the Langley 7×11-in. Low-Speed Wind Tunnel, which has a 91.4 cm long test section with a cross section 17.8 cm high by 27.4 cm wide. Test Reynolds numbers Re_θ ranged 1638-2631 at midplate for freestream velocities of 13.7-27.4 m/s. At $Re_\theta = 2631$, the boundary-layer thickness was 1.09 cm at $x = 5.1$ cm and 1.60 cm at $x = 66.0$ cm ($x = 0$ is the location of the test surface leading edge). The test surface was an extension of the bottom test section floor with a boundary-layer trip installed at $x = -25.4$ cm. Direct drag and heat-transfer measurements were obtained for the nonplanar and flat-plate surfaces.

Table 1 lists some of the critical parameters for each test surface; Fig. 1 shows representative diagrams illustrating the general features of each of the four major groups of surfaces studied. Riblets are surfaces with very small triangular grooves aligned with the freestream direction; oscillating transverse curvature surfaces have rounded longitudinal grooves that are considerably larger than riblets; wavy walls are surfaces having wavelengths the order of δ and wave heights the order of 2-3% δ, with waviness running transverse to the flow; and micro air bearings are surfaces with closely spaced transverse grooves perpendicular to the mean freestream flow.

Planform average heat-transfer measurements were obtained using a common heater element that had been designed and fabricated to provide a calculable convective heat energy output (after correction for conduction, radiation, and storage) through each of the test models at each test velocity. Area arrays of 11 thermocouples embedded 0.19 cm

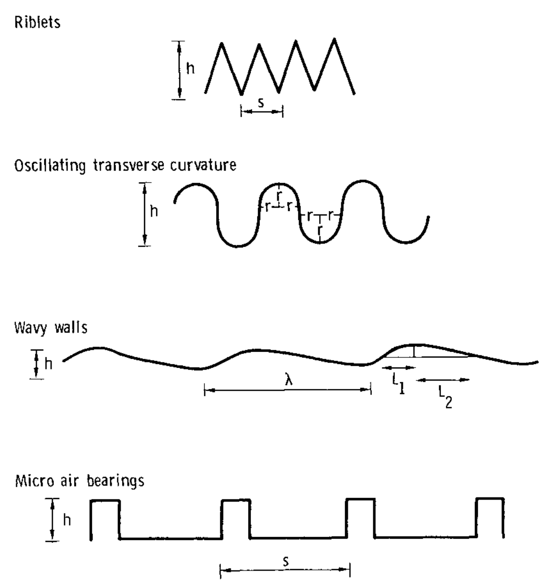

Fig. 1 Typical test surface designs.

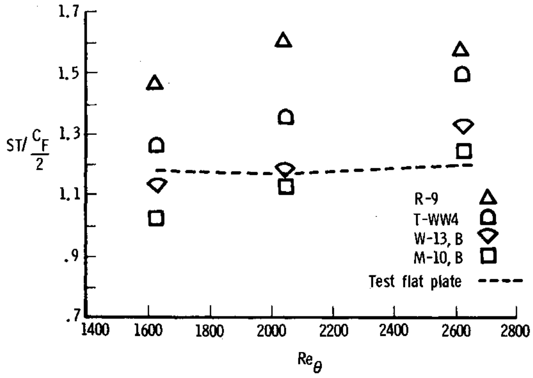

Fig. 2 Typical Reynolds analogy factors.

Table 1 Model surfaces tested

Model	h^+	s^+	h/s	A_R/A_{FP}
Riblets				
R-9	24	16	1.50	3.17
R-12	30	14	2.00	6.03
R-13	18	25	0.70	1.72
R-17	624	199	3.13	6.50
Oscillating transverse curvature				
T-WW4	47	471	0.58	1.65
T-70	97	967	0.58	1.65
Wavy walls			h/λ	
W-13a	69		0.015	1.00
W-13b[a]	72		0.015	1.00
W-16	45		0.015	1.00
W-18a	44		0.015	1.00
W-18b[a]	45		0.015	1.00
Micro air bearings			h/s	
M-3	21	34	0.62	2.25
M-5	57	198	0.29	1.57
M-10a	23	70	0.33	1.58
M-10b[a]	21	64	0.33	1.58

[a]b denotes reversed configuration.

below each test surface provided the steady-state $(T_w - T_\infty)$ distribution, which was then extrapolated and integrated over each model surface. (ΔT was nominally the order of 5°C above room temperature.) The heat-transfer coefficients for the various microgeometries were computed using the standard Newton convective heat-transfer equation for low-speed airflow,

$$Q = AH(T_w - T_\infty)$$

The heat-transfer measurements were repeatable with $\pm 2\%$.

Drag measurements were made with a free-floating air bearing drag balance. Both drag and heat-transfer measurements utilized a vacuum system incorporated in the chamber enclosing the test section to match the static pressure underneath the drag balance with the test section pressure. The motor driven rear sidewall was also adjusted in both sets of measurements to help in maintaining a near zero pressure gradient in the test section. Multiple test runs of each surface, careful model alignment, and frequent calibration checks insured drag data repeatability to within $\pm 1\%$. Net flat-plate skin-friction measurements agreed closely with classical skin-friction data at the test Reynolds number.

Results and Discussion

Drag data obtained for the present surfaces studied concur with related data.[2,3,7] Roughness parameter/drag trends include: 1) drag levels decrease with increasing h/s; 2) drag levels decrease as A_R/A_{FP} decreases; and 3) drag levels also decrease with decreasing values of h^+ below 50 or so wall units. In addition, drag levels for most of the test surfaces generally increase at characteristic rates as U_∞ increases.

Selected values of the Reynolds analogy/heat-transfer efficiency parameters are shown in Fig. 2. The experimental flat-plate Reynolds analogy factor from this study, as indicated by the dashed line on the figure, varied 1.17-1.20 throughout the test Reynolds number range; the best curve fits for experimental and theoretical Reynolds analogy factors in the literature yield 1.16 for the flat-plate Reynolds analogy.[8] Reynolds analogy factors for the micro air bearings were determined to be no better than those for the flat-plate reference. Wavy wall surfaces exhibited heat-transfer efficiency increases of up to 12% above the flat plate at the higher Re_θ. Oscillating transverse curvature produced Reynolds analogy factor increases of up to 25% above the flat plate, whereas some riblet surfaces produced factors 36% above the flat plate. All of the heat-transfer efficiency data increase to some degree with increasing U_∞ throughout the test range.

All cases in which the Reynolds analogy/heat-transfer efficiency factors are greater than the flat-plate values indicate that the associated heat-transfer increases are greater than the drag increases. The most significant Reynolds analogy factor increases noted during this experiment result from the nonconventional drag characteristics of the relevant surfaces in addition to a heat-transfer augmentation (experimental Reynolds analogy factors are directly proportional to Q/D). The riblet surfaces, which produced the highest heat-transfer efficiencies, are documented drag reducing surfaces (absolute drag levels reduced below the flat plate). The oscillating transverse curvature surfaces exhibit a trend of decreasing drag with increasing speed, which coincides with the heating rate increases with speed to produce Reynolds analogy factors consistently above the flat-plate predictions.

In conclusion, these data suggest that certain types of nonplanar surface microgeometries will increase turbulent Reynolds analogy factors significantly above flat-plate levels. In several cases, the observed elevated heat-transfer efficiencies represent the combined effects of both heat-transfer increases and drag decreases. Further work is needed to apply the surface concepts considered in this study to heat exchangers. Basically, this research would suggest decreases of the order of $+20\%$ in heat exchanger volume, cost, and weight for designs with extensive planar surfaces.

References

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