

Effects of a Kind of Surface Groove on Flow Loss in Both Rectangular and Circular Ducts at Different Reynolds Numbers (Postprint)

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Abstract

As one of the key units of space CCD camera, the temperature range and stability of CCD components affect the image's indexes. Reasonable thermal design and robust thermal control devices are needed. One kind of temperature control loop heat pipe (TCLHP) is designed, which highly meets the thermal control requirements of CCD components. In order to study the dynamic behaviors of heat and mass transfer of TCLHP, particularly in the orbital flight case, a transient numerical model is developed by using the well-established empirical correlations for flow models within three dimensional thermal modeling. The temperature control principle and details of mathematical model are presented. The model is used to study operating state, flow and heat characteristics based upon the analyses of variations of temperature, pressure and quality under different operating modes and external heat flux variations. The results indicate that TCLHP can satisfy the thermal control requirements of CCD components well, and always ensure good temperature stability and uniformity. By comparison between flight data and simulated results, it is found that the model is to be accurate to within 1 degrees C. The model can be better used for predicting and understanding the transient performance of TCLHP.

Full Text

Preamble

Effects of a Kind of Surface Groove on Flow Loss in Both Rectangular and Circular Ducts at Different Reynolds Numbers

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Pipes are widely used to transport gas, oil, and water in industrial applications, and drag reduction in pipes has become an increasingly important research focus for energy savings. Previous studies have indicated that non-smooth surfaces with special structures can reduce flow losses. This paper presents an experimental investigation of the effects of a particular surface groove on drag in both rectangular and circular ducts across different Reynolds numbers. In the rectangular duct experiments, total pressure was measured at both inlet and outlet, while static pressure on the wall was measured on surfaces with smooth and grooved films, respectively. In the circular duct experiments, a boundary layer pressure probe measured the total pressure distribution at both inlet and outlet, and four taps at each location measured static pressure. The loss coefficient was used to evaluate the groove effects on drag reduction. Experiments were conducted over a Reynolds number range from 1.28×10^4 to 2.57×10^4 . Results show a maximum drag loss reduction of approximately 2.4% in the rectangular duct at a Reynolds number of 2.4×10^4 . A 10% reduction in pipe pressure loss due to the grooved surface was measured in the circular duct at a Reynolds number of 3.0×10^4 .

Keywords: drag reduction, surface groove, rectangular duct, circular duct

Introduction

Drag reduction in pipeline transportation has emerged as a major research focus across industries. Surface grooves represent one method for reducing flow losses, and the study and development of groove structures for loss reduction and energy savings has attracted considerable attention from researchers in recent years.

Grooved surfaces were originally developed at NASA Langley Research Center in the late 1970s to reduce aerodynamic turbulent skin friction. Based on NASA Langley's work (Walsh [?]), many streamwise microgrooved surfaces were tested to verify drag reduction effects, with results showing 7–8% drag reduction from sharply peaked, symmetric V-groove riblets. However, practical application of V-groove riblets was limited due to their susceptibility to wear.

Gong Wu-Qi [?] investigated the drag reduction mechanism of riblets and found that grooved structures could alter boundary layer characteristics, with riblets reducing the averaged turbulent kinetic energy through drag reduction.

While grooved surfaces have been studied extensively in external flows, investigations of their effects on internal flows remain limited. Bushnell [?] noted that riblet effects on internal flows may differ from those on external flows due to mass flow constraints. Rohr [?] discovered that drag-reducing performance of riblets was similar across a wide variety of internal and external flows, though further research on grooved structures in internal flows is needed.

Moore and Lawson [?] studied drag reduction in a rectangular duct using riblets, finding a maximum drag reduction of 10% in fully developed turbulent flow—greater than the 6–8% reduction observed in external flows. They also found

that riblets delayed transition by 2–4% and extended the transition process length.

Ma Hongwei [?] conducted an experimental study of turbulent boundary layers on both grooved and smooth surfaces, with results indicating that grooves can effectively reduce the accumulation of low-speed fluids and directly affect flow structures in the sublayer of the boundary layer, modulating the flow field up to the buffer and logarithmic regions by restraining vortex development and interaction. However, validation of this groove structure's drag reduction performance in pipe flow remains incomplete.

Building on these previous results, this research focuses on the effects of surface grooves on drag reduction in both rectangular and circular ducts. A pipe test rig was constructed with a high-accuracy, high-spatial-resolution flow measurement system including a boundary-layer pressure probe, traverse mechanism, pressure transducers, and data acquisition hardware and software. In the rectangular duct, total pressure was measured at both inlet and outlet, while static pressure was measured on walls with smooth and grooved films. Loss coefficient and loss reduction efficiency were employed to analyze experimental results. In the circular duct experiments, pipe models with smooth and grooved surfaces were designed and manufactured, with total pressure measured at both inlet and outlet using a boundary layer pressure probe attached to a traverse mechanism to scan the outlet. Four taps at inlet and outlet measured static pressure.

Experimental Facility and Test Technique

Rectangular Duct

Airflow at speeds ranging from 7 to 12 m/s was provided by an axial flow fan with a power of 65 W, rotating speed of 2870 r/min, and mass flow rate of 0.08–0.13 kg/s. The Reynolds number range in the experiment was 1.28×10^5 to 2.57×10^5 . A schematic diagram of the test rig is shown in Fig. 1 [Figure 1: see original paper].

The airflow entered the inlet duct and passed through a contraction section with a shrink angle of 4.6° . The flow became fully developed at cross-section A1 after passing through straightening gratings. The working section was attached to the straightening section, with dimensions of 30 mm \times 200 mm and a length of 1300 mm. The ambient temperature was maintained constant during testing.

Eight static pressure holes (0.5 mm diameter) were located on the working section surface at 100 mm intervals for installing eight static pressure probes. On cross-section A2, five total pressure probes were configured at different positions, as shown in Fig. 2 [Figure 2: see original paper].

The pressure sensor measuring range was -1000 Pa to $+1000$ Pa with an accuracy of 0.01%. An AT-MIO-64F-5 data acquisition card from National Instruments was employed, with a sampling frequency of 20 kHz. The experimental process was controlled using LabVIEW software.

The non-dimensional riblet height h was 2.24, while the non-dimensional riblet width s was 11.2, defined based on the characteristic scales of the test model.

Circular Duct

The circular duct, shown in Fig. 3 [Figure 3: see original paper], was attached to the contraction section of a wind tunnel driven by a roots blower. The duct model was 600 mm long with an inner diameter of 115 mm. Airflow was provided by the wind tunnel at three speeds: 10 m/s, 20 m/s, and 30 m/s. The ambient temperature was 27°C.

Total pressure at the inlet was measured by a single total pressure probe. As shown in Fig. 4 [Figure 4: see original paper], a boundary layer pressure probe measured the total pressure distribution at the outlet, with a station distance of 0.2 mm near the inner wall and 1-2 mm in the mainstream region. The traverse mechanism accuracy was 0.02 mm. Four taps (0.5 mm diameter) at both inlet and outlet measured static pressure, with all pressure taps connected to pressure transducers.

Groove Structure

This study investigated the effect of a specific groove structure on flow loss in pipes. Fig. 5 [Figure 5: see original paper] shows the groove geometry. The groove structure was attached to the internal surfaces of the ducts, and its loss reduction effect was compared with that of smooth surfaces.

Results and Discussions

Rectangular Duct

Fig. 6 [Figure 6: see original paper] shows the static pressure distribution along the pipeline with a smooth internal surface, measured on both the upper and side surfaces of the inner wall. When both surfaces were smooth, the static pressure drop along the pipeline was nearly identical, confirming consistent experimental conditions and verifying flow field uniformity.

To obtain universally applicable results, dimensionless analysis was employed. The loss coefficient was calculated to quantify flow loss along the duct model at specific Reynolds numbers. Fig. 7 [Figure 7: see original paper] compares the loss coefficient distribution for smooth and grooved surfaces at different Reynolds numbers.

As shown in Fig. 7, within the test range of 1.28×10^4 to 2.57×10^4 , several distinct regimes were observed. For $Re < 1.4 \times 10^4$, the smooth surface exhibited lower loss reduction. Between $Re = 1.4 \times 10^4$ and 1.5×10^4 , the difference between smooth and grooved surfaces was minimal. For Re between 1.5×10^4 and 1.85×10^4 , the smooth surface showed smaller loss reduction. As Re increased from 1.85×10^4 to 2.0×10^4 , loss reduction for both surfaces was nearly equivalent.

For $Re > 2.0 \times 10^4$, the loss reduction effect became more pronounced, reaching a maximum efficiency of 2.3-2.4% at $Re = 2.4 \times 10^4$.

Circular Duct

To apply experimental results to practical applications, dimensionless analysis was conducted using the loss coefficient to quantify flow loss along the duct model. Loss coefficients were calculated for smooth and grooved surfaces at three Reynolds numbers: 7.74×10^3 , 1.5×10^4 , and 3.0×10^4 .

Fig. 8 [Figure 8: see original paper] and Fig. 9 [Figure 9: see original paper] demonstrate the loss coefficient distributions at the duct outlet for smooth and grooved internal surfaces, respectively, while Fig. 10-12 [Figure 10: see original paper][Figure 11: see original paper][Figure 12: see original paper] show comparative effects at each Reynolds number. The overall loss coefficient was obtained through area averaging, with results shown in Fig. 13 [Figure 13: see original paper]. Under all three conditions, the grooved surface exhibited smaller loss coefficients than the smooth surface, with the most pronounced difference occurring at $Re = 3.0 \times 10^4$.

Loss reduction efficiency was employed to evaluate the drag reduction effect of the grooved surface relative to the smooth surface. As shown in Fig. 14 [Figure 14: see original paper], the grooved surface reduced losses by 5.7%, 5.2%, and 10% at Reynolds numbers of 7.74×10^3 , 1.5×10^4 , and 3.0×10^4 , respectively.

Conclusions

This paper experimentally investigated flow losses in rectangular and circular duct models with smooth and grooved surfaces. The effects of the grooved structure on drag reduction were successfully demonstrated.

In the rectangular duct experiments, total pressure was measured at both inlet and outlet, while static pressure was measured along the pipeline with smooth and grooved films. In the circular duct experiments, a boundary layer pressure probe measured the total pressure distribution, and static pressure was measured at inlet and outlet.

Results indicate that this grooved surface can effectively reduce pipe pressure loss. In the rectangular duct, the loss reduction effect became more significant when $Re > 2.0 \times 10^4$, reaching 2.3-2.4% efficiency at $Re = 2.4 \times 10^4$. In the circular duct, the grooved surface loss coefficient was smaller than the smooth surface coefficient at all three tested Reynolds numbers (7.74×10^3 , 1.5×10^4 , and 3.0×10^4), with loss reduction efficiencies of 5.7%, 5.2%, and 10%, respectively. The maximum loss reduction efficiency of 10% was achieved at $Re = 3.0 \times 10^4$.

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