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Flow patterns and critical criteria of thermally stratified shear flow in braided rivers

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Abstract

Flow characteristics of thermally stratified shear flow in braided rivers are particularly complicated and poorly understood. In this study, a series of typical flow patterns was examined and their critical criteria were determined. Four flow patterns were identified: mixed, locally unstable, continuously stratified, and two-layer flow. Temperature distributions of the four types of flow patterns were analyzed and compared. The critical Froude numbers for unstable flow, F_{Dcr1}, and stable flow, F_{Dcr2}, were determined to be 6 and 1, respectively, and comparison of F_{Dcr1} and F_{Dcr2} to the peak Froude numbers, F_{D1} at the outer bank and F_{D2} at the inner bank along the anabranch, allowed the flow patterns to be assessed. Then, a discriminant based on initial Jeffreys-Keulegan stability parameters was established to distinguish the flow stages from two-layer flow to completely mixed flow. It is indicated that the three critical Jeffreys-Keulegan parameters increased with the diversion angle of braided rivers. Results also show that, compared to the stratified flow in straight and curved channels, it was more difficult for braided stratified flow to maintain as two-layer flow, and it more easily became mixed flow. Consequently, empirical expressions for stability criteria of the thermally stratified shear flow in braided rivers are presented.

Keywords: Braided river; Critical criterion; Empirical formula; Flow pattern; Temperature distribution; Thermally stratified flow

1. Introduction

When a vertical density gradient is maintained along a stream, and the density remains stratified throughout the channel, the flow is considered stable stratified. Otherwise, it is considered mixed flow. Within stable stratified flow, there is an extreme state, i.e., two-layer flow, where matter and energy exchanges rarely occur between the upper and lower fluids.

Stratified flow in single straight or curved channels has been widely studied (Donda et al., 2015; García-Villalba and Del Álamo, 2011; Huai et al., 2010; Schiller and Sayre, 1975; Schmid et al., 2004; Williamson et al., 2015; Zeng and Huai, 2005). The flow structure and temperature distribution of stratified flow in a single channel are relatively simple compared to those in braided rivers. The hydraulic phenomena in the case when stratified flow passes through a braided river are complex, and have been studied little, aside from some research on the homogeneous flow structure of braided rivers (Gu et al., 2014, 2015; Hua et al., 2009;

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Richardson and Thorne, 1998, 2001; Yu et al., 2007). Hua et al. (2009) conducted physical model experiments on homogeneous flow in a typical braided river, and they observed two circulation cells of opposite rotation and a separation zone occurring near the outside wall in the entrance region of the anabranch. Gu et al. (2015) investigated flow structures of stratified flow in a braided river with three discharges experimentally. However, stratified flow patterns for different diversion angles and inflow ratios have not been systematically studied.

Research on stability criteria, in the form of dimensionless parameters, such as the Jeffreys-Keulegan stability parameter, Richardson number, and densimetric Froude number, has mainly focused on single channel cases. Keulegan (1949) experimentally investigated the stability of two-layer viscous stratified flow. Following Jeffreys (1925), Keulegan (1949) derived the Jeffreys-Keulegan stability parameter as follows:

$$\Theta = \frac{\left(\nu g \Delta\rho / \rho_{\mathrm{u}}\right)^{1/3}}{V} \tag{1}$$

where ν is the kinematic viscosity, g is the gravitational acceleration, ρ_{u} is the fluid density of upper light flow, $\Delta\rho$ is the density difference across the interface, and V is the velocity of upper light flow.

Keulegan (1949) found that if the Reynolds number of the upper fluid was less than 450, for two-layer flow the critical Θ was 0.127. Otherwise, the critical Θ was 0.178, which meant that the critical Θ depended on fluid viscosity as well as the turbulent state between the two fluids. Sherekov et al. (1971) determined the critical Θ for each stage from two-layer flow to completely mixed flow, with $\Theta > 0.188$ for two-layer flow and $\Theta < 0.085$ for completely mixed flow. Hua and Chu (2008) conducted a large number of physical experiments in straight and curved channels with different diversion angles to explore the critical initial Jeffreys-Keulegan stability parameters, $\Theta_{0\mathrm{cr1}}$ and $\Theta_{0\mathrm{cr2}}$ (for mixed flow, the initial Jeffreys-Keulegan stability parameter Θ_0 is smaller than $\Theta_{0\mathrm{cr1}}$, and for two-layer stratified flow, Θ_0 is greater than $\Theta_{0\mathrm{cr2}}$), and found that, for straight and curved channels of 45°, 90°, and 180°, $\Theta_{0\mathrm{cr1}} = 0.04$, 0.05, 0.06, and 0.07, and $\Theta_{0\mathrm{cr2}} = 0.06$, 0.07, 0.08, and 0.09, respectively.

Many investigators have contributed to our understanding of the stability conditions of stratified flow using the Richardson number (Drazin, 1958; Galperin et al., 2007; Miles, 1961; Rohr and Van Atta, 1987; Taylor, 1931) and densimetric Froude number (Chu et al., 2008; Harleman, 1961; Jin and Zhang, 1992; Schiller and Sayre, 1975). Thus, the stability properties of stratified flow in straight and curved channels are understood, and corresponding stability criteria are available. However, the unstable state of stratified shear flow through braided rivers, a common natural river pattern, remains unclear. Some special and unknown unstable processes of stratified flow occur due to the suddenly increased cross-section at the bifurcation, the subsequent separation, and the streamline curve along each anabranch. Therefore, it is necessary to examine each stage from two-layer flow to completely mixed flow in braided rivers and explore the stability characteristics and criteria, as a requirement for the study of stratified flow.

In this study, flow patterns of thermally stratified shear flow in braided rivers with different diversion angles were explored, and corresponding relationships between stability criteria and the diversion angle were derived.

2. Model of stratified flow in braided rivers

2.1. Experimental setup

The physical model of a symmetrical braided river with a middle bar that had a diversion angle of 90° is shown in Fig. 1. Two independent inflow systems, cold and warm water, were used to generate the thermally stratified flow. The flume consisted of a straight introduction segment (5 m long), braided segment (1.71 m long), and straight effluent segment (5 m long). Symmetrical anabranches 1 and 2 were separated by the middle bar, and L1 through L9 and R1 through R9 were typical cross-sections for analysis in anabranches 1 and 2, respectively. The bank near the middle bar was the inner bank, while the other was the outer bank. The widths of the straight segment and anabranches 1 and 2 were B_0, B_1, and B_2, with $B_0 = 0.28$ m, and $B_1 = B_2 = 0.2$ m. A thin glass plate was set in the straight introduction segment at a height 0.15 m from the bottom to separate the upper (warm) and lower (cold)

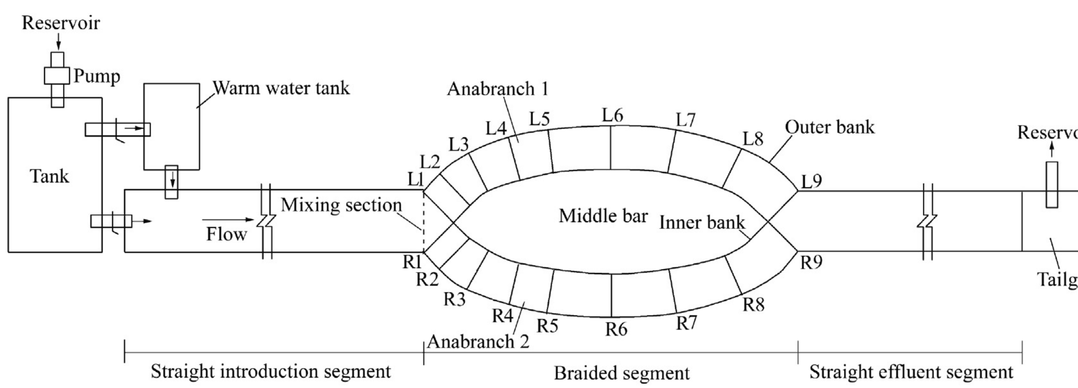

Fig. 1. Sketch of braided river model.

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