INTISARI

Aliran *annular* merupakan salah satu rezim aliran dua fase yang kompleks, ditandai oleh keberadaan film cair pada dinding pipa dan inti gas yang membawa *entrained droplets*. Meskipun telah banyak diteliti, mekanisme pembentukan aliran ini, khususnya selama fase transisi dari *stratified flow*, masih menyisakan berbagai pertanyaan. Oleh karena itu, penelitian ini bertujuan untuk menginvestigasi secara visual dan kuantitatif mekanisme terbentuknya aliran annular air-udara dalam pipa horizontal dengan pendekatan *image processing*.

Visualisasi dilakukan menggunakan kamera kecepatan tinggi untuk merekam perilaku antarmuka secara spasial-temporal, sedangkan pengolahan citra digunakan untuk memperoleh profil ketebalan film cair. Pengukuran tekanan dilakukan secara simultan untuk mengamati perubahan gradien tekanan selama transisi aliran. Hasil pengamatan menunjukkan bahwa transisi dari stratified ke annular berlangsung bertahap, dimulai dari stratified smooth, berkembang menjadi gelombang 2D dan 3D, kemudian *roll wave*, *disturbance wave* (ED + DW), dan *pseudo slug*, sebelum mencapai pola *annular* yang stabil.

Ketebalan *liquid film* mengalami perubahan signifikan selama transisi dari aliran *stratified to annular*. Pada fase awal *stratified smooth* pada J_L = 0,01 dan J_G = 4 m/s memiliki rata-rata ketebalan film di angka 5,245 mm. Seiring peningkatan J_L, ketebalan film meningkat secara bertahap hingga mencapai nilai maksimum 7,681 mm pada pola *pseudo slug* saat J_L = 0,3 m/s dan J_G = 4 m/s. Saat J_G meningkat, gaya geser dari fase gas mulai mendominasi dan mendorong film cair ke arah dinding samping pipa, sehingga film menjadi semakin tipis. Pada kondisi J_G = 14 m/s dengan J_L = 0,02–0,3 m/s, ketebalan film pada fase *annular* memiliki rentang 4,340–5,024 mm. Sementara itu, Gradien tekanan meningkat seiring bertambahnya J_G dan J_L selama transisi aliran. Nilai terendah tercatat pada pola *stratified smooth* sebesar 0,03 kPa/m pada kondisi J_G = 4 m/s dan J_L = 0,01 m/s. Nilai ini meningkat bertahap pada pola *stratified* 2D, 3D, *roll wave*, ED + DW hingga mencapai *pseudo slug*, seiring dengan pertumbuhan gelombang dan meningkatnya intensitas aliran. Nilai maksimum gradien tekanan mencapai 5,43 kPa/m pada pola *annular* pada J_G = 14 m/s dan J_L = 0,3 m/s. Penelitian ini memberikan pemahaman mendalam mengenai dinamika transisi aliran annular, serta menunjukkan bahwa metode *image processing* merupakan pendekatan non-invasif yang efektif untuk studi visual dan kuantitatif aliran dua fase.

Kata kunci: aliran dua fase, *annular flow*, *transition flow*, *high-speed video camera*, *image processing*, gradien tekanan.

ABSTRACT

Annular flow *is one of the most complex flow regimes in two-phase systems, characterized by the presence of a liquid film along the pipe wall and a gas core carrying entrained droplets. Although it has been extensively studied, the formation mechanism of this flow—especially during the transition phase from stratified flow—remains an open question. Therefore, this study aims to visually and quantitatively investigate the formation mechanism of water-air annular flow in a horizontal pipe using an image processing approach.*

Flow visualization was performed using a high-speed video camera to capture the spatio-temporal behavior of the gas–liquid interface, while image processing was applied to extract the liquid film thickness profile. Simultaneous pressure measurements were conducted to observe the evolution of the pressure gradient during flow transition. The observations reveal that the transition from stratified to annular flow occurs progressively, starting from stratified smooth, followed by the development of 2D and 3D waves, then roll waves, disturbance waves (ED + DW), and pseudo slugs, before reaching a stable annular pattern.

The liquid film thickness undergoes significant changes throughout the transition from stratified to annular flow. In the initial stratified smooth phase ($J_L = 0.01$ m/s, $J_G = 4$ m/s), the average film thickness was recorded at 5.24 mm. As J_L increases, the film thickness gradually rises, reaching a peak of 7.68 mm during the pseudo slug pattern at $J_L = 0.3$ m/s and $J_G = 4$ m/s. With increasing J_G, the gas-phase shear force becomes dominant, pushing the liquid film toward the pipe walls and causing it to thin. Under conditions of $J_G = 14$ m/s and $J_L = 0.02$–0.3 m/s, the film thickness in the annular flow regime ranges from 4.340 to 5.024 mm. Meanwhile, the pressure gradient also increases with higher J_G and J_L during the flow transition. The lowest value was found in the stratified smooth pattern at 0.03 kPa/m ($J_G = 4$ m/s, $J_L = 0.01$ m/s). It then increases progressively through the stratified 2D, 3D, roll wave, and ED + DW patterns, in line with wave growth and increasing flow intensity. The highest pressure gradient was recorded at 5.43 kPa/m during the annular flow at $J_G = 14$ m/s and $J_L = 0.3$ m/s. This study contributes to a deeper understanding of annular flow transition dynamics and demonstrates that image processing is an effective, non-invasive approach for the visual and quantitative investigation of two-phase flow interfaces.

Keywords*: two-phase flow, annular flow, transition flow, high-speed video camera, image processing, pressure gradient.*