博　士（工　学）　ハミドレザ　ジャムシドニア

学 位 論 文 題 名

Experimental Investigation of Flow Strcuture around a Standing Baffle in Rectangular Open Channels by Ultrasound Doppler Velocimetry

（超音波ドップラー流速測定法による開水路内のバッフル周り流れ構造に関する実験的研究）

学位論文内容の要旨

The spatial and temporal structure of flow around an intermediate standing baffle (step) in rectangular open channels has been investigated experimentally in detail. Understanding flows over baffles and steps is of great value due to their application in a large number of engineering configurations. Flow over a baffle can be considered as an extreme combination of flows over backward- and forward-facing steps. Thus although the geometry of a baffle is simple, the flow over it has diversified time-dependent features and complex flow structures. Importantly streamlines are not parallel to the wall at the separation point. Thus the impinging flow at immediate upstream of the baffle has two dimensional characteristics. From another perspective, since performance of a settling tank is heavily dependent on its flow field, provision of a baffle or deflector in a settling tank to modify the flow field and consequently to improve the efficiency of it has been investigated by several researchers as a method for flow control. Thus it is important to investigate hydrodynamics and structure of flow field in a baffled tank in detail. Relatively few detailed measurements of flow field characteristics of such tanks are available in the literature. Furthermore, most of them are lacking the concept that the flow has a strongly spatio-temporal nature and only qualitative description of the flow field has been made.

Therefore, in the present study a comprehensive set of systematic experimental investigations of the effect of a standing baffle on the structure of flow and spatio-temporal characteristics of flow around it has been made in a quantitative manner.

A detailed investigation of velocity measurement obtained by a 3D ADV(Acoustic Doppler Velocimeter) in a primary rectangular sedimentation open channel with a rather low Reynolds number turbulent flow revealed the existence of a clear peak structure in the smoothed space-averaged power spectra of streamwise and vertical velocity components at upstream of the baffle. It was found that the baffle effects the stream wise energy dissipation and not on the vertical energy dissipation by damping out the peak structure of streamwise velocity component at downstream of it but not affecting the peak structure of the vertical component.

Considering the importance of the problem and the strong spatio-tempral nature of flow, Ultrasonic Velocity Profiler (UVP) has been successfully applied to investigate the flow structure over a baffle in a set of systematic experiments.

Due to the capability of UVP in the non-invasive measurement of flow velocities along its measuring line simultaneously, a single transducer, slightly inclined from the vertical direction and inserted into the water near the free surface, was scanned along the channel to extract the spatio-temporal flow structure and its characteristics at various Re numbers. Various spatial distributions such as on-axis time-averaged velocity profiles and relative turbulent intensities at different streamwise measurement sections indicate the flow structure of uprising flow at upstream of the baffle, vortex shedding and flow separation, change of the effective cross-section just behind the baffle and recirculation flow at its downstream. These phenomena are also reflected in the peak values of the relative turbulent intensity profiles. Spatio-temporal on-axis velocity field of up- and downstream sections confirms

the existence of periodic change of flow direction near the baffle' s edge at downstream sections. The existing flow phenomena were categorized by capturing four types of Phenomenological Zero Crossing Points (PCP). Additionally, distribution of the space-dependent power spectra indicates the existence of some peak structures concentrated near the baffle' s edge for downstream sections whereas such peak structures have not been observed for the upstream sections. Also for downstream sections mainly the existence of peak values in the space distribution of two frequency modes could be confirmed which can be attributed to the vortex shedding due to the existence of the baffle.

By aligning a transducer in the vertical direction spatio-temporal structure of vertical velocity field was successfully captured and quantified using UVP. For the upstream of the baffle structure of uprising flow was obtained. At its downstream vortex shedding, reverse flow region were captured. The most significant feature of the relative turbulent intensity profiles was found to be the pronounced peak values (like a bump) near the baffle' s edge. They can be mainly associated with the existence of the vortex shedding behind the baffle. This effect was also reflected as local maxima (a kind of bump with a value near zero and a high value of relative turbulent intensity) in the mean velocities profiles at similar heights just above the baffle' s edge which in turn is a representative of the vortex shedding and periodicity behind the baffle. The mean flow structure also provides a detailed picture on the spatial velocity variations (or degree of spatiality) in quantitative manner. Such information is also very useful when we look at the problem from the view point of sedimentation.

Behind the baffle development of time dependent vertical flow due to vortex shedding was quantified as periodicity in the spatio-temporal distributions of vertical velocities. Space-dependent power spectra of vertical velocities reveals the existence of some peak structures over space and near the baffle edge for downstream sections of the baffle whereas for the upstream ones such peak structures have not been observed. Also the existence of dominant peak values mainly in the space distribution of two frequency modes was observed downstream of the baffle and in the vicinity of baffle height. The existence of peak structures in space-dependent power spectra and peak values in two frequency modes downstream of the baffle are in agreement with the appearance of the peak values in the relative turbulence intensity profiles and the periodic behavior of spatio-temporal velocity distribution for the corresponding sections near the baffle edge. As a result such peak structures can be attributed to the vortex shedding due to the existence of the baffle. At the same time, the results corresponding to vertical structure of flow confirm the findings of inclined experiments.

Additionally, by using two vertically positioned ultrasound transducers operating in the multiplexing mode which were inserted into water near free surface flow field around the baffle was successfully characterized based on the degree of correlation between vertical velocity fluctuations of flow at points located at up- and downstream sections of the baffle. Contour maps of the peak of the absolute value of the normalized cross-correlation coefficients between vertical velocity fluctuations at points located on an upstream measuring line with those on a downstream measuring line were used to evaluate the effect of the baffle on their degree of correlation. Existence of two regions with various characteristics has been confirmed. In one region extended from the proximity of the baffle edge to the channel bed the degree of correlation between vertical velocity fluctuations at baffle' s up- and downstream points is strongly damped out. Furthermore, the existence of a peak region inside the other region which is extended from the free surface to baffle' s edge has been confirmed. In this zone the degree of correlation decreases gradually from the peak region to the proximity of the baffle edge which is indicative of baffle' s effect on the flow structure in its downstream. Also the decrease in the correlation degree from the peak to the free surface was captured which may be attributed to the effect of free surface.

As the next step, two UVP transducers inserted into the water near the free surface and were positioned at optimized different angles (-30° , 30°) against the flow direction. They were displaced by an accurate traversing system to capture the vector velocity at various spatial points around the baffle. Thus flow field could be constructed around the baffle by forming the velocity vectors at each crossing of two measuring lines. Consequently, time-averaged velocity vector field around the baffle could be successfully obtained. Profiles of the time-averaged velocity components, relative turbulent intensities as well as Reynolds stresses indicate, quantitatively, the change of flow structure from up- to downstream of the baffle. Uprising flow at upstream and indications of existence of vortex shedding at downstream of baffle were found. At downstream of baffle development of flow pattern and a large recirculation region could also be captured and position of the reattachment point could be determined. It was found that at baffle' s upstream the profiles of relative turbulent intensities are almost uniformly distributed over channel' s depth but at its downstream indications of high values of relative turbulent intensities could be observed which can be as a result of vortex shedding. In addition, the Reynolds stress

profiles were estimated. At downstream of the baffle indications of some non-uniformities could be observed which can be as a result of the existence of the vortex shedding and separation at downstream of the baffle. It was also found that the results concerning single line measurements are generally in agreement with the vector measurements.
The study also shows promising applications for the measurement of particle-laden flow structure by UVP as it is applicable to opaque liquids and thus the same methodology can be used. The understanding obtained from this study and its methodology is also expected to greatly benefit the design in industrial applications specifically when the flow is opaque and has two-dimensional characteristics.

学位論文審査の要旨

主　査　　教　授　　村　井　祐　一
副　査　特任教授　　武　田　　　靖（東京工業大学
総合研究院）
副　査　　教　授　　藤　川　重　雄
副　査　　教　授　　大　島　伸　行
副　査　准教授　　坪　倉　　　誠

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Experimental Investigation of Flow Strcuture around a Standing Baffle in Rectangular Open Channels by Ultrasound Doppler Velocimetry

（超音波ドップラー流速測定法による開水路内のバッフル周り流れ構造に関する実験的研究）

開水路の流れは，水面の挙動と壁面の境界層の干渉に関する問題として位置づけられ，流体力学的に長い歴史をもつ研究対象である．その開水路の中にバッフル（じゃま板）を設けると，その影響領域がどの程度形成され，乱流の特性がどのように変化するかについて，幅広い工学的応用の観点から興味が持たれてきた．例えば浄水設備における沈降分離の促進や，河川・港湾施設における不純物・堆積層の輸送または混合に直結する基本的な流れの現象である．また，バッフル周りの流れはバックステップ流れとフォワードステップ流れの組み合わせとして理解することが可能で，その場合の時空間的な乱流変動特性の定量的調査は，流体力学的にも広範で普遍的な知益を提供する模範的な流れでもある．本研究論文ではその流動場の時空間構造を定量化する流体計測手法として超音波ドップラー流速分布計測法（Ultrasound Doppler Velocimetry, UDV）を活用あるいは拡張して利用し，バッフル前後の乱流特性の差異を検出することにより，開水路中のバッフルが新たに駆動する流れの構造を詳しく考察したものである．

本研究の内容は以下の6章にまとめられている．

第1章においては，本研究の背景，工学的な研究の需要性，流体力学的な問題設定の特徴について述べている．それに基づき，本研究の目的と実験的研究の計画について示している．特に本研究ではUDVを高精度な定量計測手段として一貫して利用する計画から，それに先だってレーザーによる流れの可視化を実施し，その結果をもとにバッフル周りの流れ場の定性的な特徴を予め抽出している．また，開水路の深い位置にバッフルを設置する条件を標準的な実験条件とすることについて，浅い場合との対比を示す可視化結果を示し，本研究で扱う実験条件の選定の根拠を説明している．

第 2 章においては,UDV の一種である音響ドップラー流速計 (Acoustic Doppler Velocimeter, ADV) の利用について, その原理を含めた解説から始まっている.ADV は比較的低周波数の超音波パルスを 3 方向から発射し, そのビームの交点において流速の三成分を計測する方法である. この方法を利用することで, バッフルの上流と下流における乱流エネルギースペクトルを比較し, その結果, 上流に存在する開水路特性に起因した特定の周波数の速度変動が下流で消滅することを示している. また, 主流方向の速度変動がバッフルによって下流で減衰するのに対して, 鉛直方向の乱れは消散しにくいことを明らかにした. またこれらの結論を得るうえで ADV の計測ノイズおよび乱流変動の識別について独自のノイズ除去スキームを導入したことについても実験データの後処理手段として詳しく記載されている.

第 3 章においては,UDV の発展型機種である超音波ドップラー流速分布計 (Ultrasound Velocity Profiler, UVP) の利用にあたって, その計測原理と利点についての説明から始まっている.UVP の特徴は超音波パルスの伝播線上の流速分布を高速にサンプリングすることが可能な点であり, バッフル周りの流れの時空間構造を定量的に可視化できることを述べている. この章では UVP の利用によって, バッフル上端からの準周期的な渦放出を捕らえ, そのレイノルズ数依存性と, 下流への渦運動の持続について考察を加えながら詳述している. またバッフル背後の剥離・循環流について,UVP が出力するゼロクロス点の情報からその空間構造を把握する方法を提唱している.

第 4 章においては,UVP の計測線を完全に鉛直に設置する条件に特化して得られる流動場の特徴について述べている. まずその冒頭で, そのような計測条件に設定することが, 粒子の沈降分離技術の効率評価に関わって具体的に重要性を持つことを説明している. その後, それによって計測された鉛直方向の流速成分の時間平均と分散から, 相対乱流エネルギーを定義し, それがバッフル上端から放出される渦列のもつ流線上で極大値をもつことを示している. さらに UVP による時空間流速分布から, バッフル上流と下流の流速の時間変動特性に関する相互相関をバッフル高さ方向の空間分布として導いている. 以上の結果から乱流特性がバッフル背後の再循環流領域とそれより上側外層の準ポテンシャル流領域に分離して評価でき, また, 沈降分離における粒子挙動の制御の観点でも, この知見が適用できることを提示している.

第 5 章においては,UVP の計測線を異なる角度で二つ設置することにより, その交点での流速 2 成分と, その周囲の流速 1 成分を時間の関数として計測することができる二方向ステレオ UVP について述べている. 同時に, 具体的にそのようなステレオ配置のデバイスを設計・製作・試験し, 原理的な確認と性能の評価を行っている. この応用により, バッフルが作り出す周囲の二次元的速度ベクトル場の計測に成功し, そのデータ解析から, 十分に上流または下流における一次元的な流れの構造と識別する基準を定義することで, 二次元構造をもつ影響領域を定量評価している. またベクトルデータからレイノルズせん断応力など乱流統計量を算出し, バッフル上流の上昇流領域と, バッフル下流の渦列層における乱流運動量交換の特徴について明らかにしている.

第 6 章においては, 本研究の結論, 並びに UDV による二次元以上の流動場の計測について残された課題と今後の開発の方向性の提案について述べている.

以上のように本論文では, 開水路の底面に設置されたバッフルの周りに形成される流動構造について,ADV,UVP, および二方向ステレオ UVP の三つの超音波ドップラー流速計測法に基づいた計画的な実験手段により, 新たな流体力学的知見を得た. この成果は, 水処理を初めとする幅広い工学的応用技術に活かされるだけでなく, 単純形状の障害物による周囲流動場の制御を実現しようとする様々な研究の模範となる. さらに, 超音波ドップラー流速測定法 (UDV) の多次元乱流場の計測への展開に向けての基礎となる一連の実験技術を構築しており, 実験流体力学に新しい一分野を開拓す

る展開性を示している. よって著者は北海道大学博士 (工学) の学位を授与される資格があるものと認める.