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研究展望

気液二相流動系と混合系の研究展望*

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Review of Studies on Gas-Liquid Two-Phase Flow and Mixture Systems

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Gas-liquid two-phase flow and mixture systems are encountered in various industrial apparatuses and applications. The systems can be categorized as the following four : (a) the systems with heat transfer and with the flow of both gas and liquid, like boiling two-phase flow in heat exchangers, (b) the systems without heat transfer but with the flow of both gas and liquid, like adiabatic two-phase flow in oil pipe line systems, (c) the systems with heat transfer but without the flow of one of gas and liquid, like pool boiling, and (d) the systems without heat transfer and without the flow of one of gas and liquid, like aeration in chemical reaction and water purification systems. Of these, the first two categories are mainly dealt here and the relating papers reported in "Transactions of the Japan Society of Mechanical Engineers, Series B" and in "JSME International Journal, Series B" since January 2004 to August 2006 are reviewed to seek the future studies in the field of the gas-liquid two-phase flow and mixture systems.

***Key Words*:** Multiphase Flow, Gas-Liquid Two-Phase Flow, Interfacial Phenomena, Bubble, Liquid Droplet, Liquid Film, Review

1. はじめに

気液二相流動系と混合系はさまざまな産業上の装置や応用において見られ，次の四つに分類できる．(1)熱交換器内の沸騰二相流のように熱移動を伴いかつ気液両相ともに流動する気液二相流動系，(2)石油パイプラインのように熱移動を伴わないが気液両相ともに流動する気液二相流動系，(3)プール沸騰のように熱移動を伴いかつ片方の相のみが流動する気液の混合系，(4)化学反応層や浄水槽内のエアレーションのように熱移動を伴わないが片方の相のみが流動する気液の混合系，である．この展望では，2004年1月～2006年8月までに，「日本機械学会論文集B編」と「JSME International Journal, Series B」に発表された論文について，上記の4分類のうち(1)，(2)の気液二相流動系の研究を主としてレビューを行うとともに(3)，(4)の気液の混合系の研究動向にも触れて，両分野での今後の研究課題を探る．

2. 熱移動を伴う気液二相流動系

単一直管内の流れについては，同心環状流路を用いて原子炉燃料集合体内のスペーサがバーンアウトに及ぼす影響を調べた実験[(1)]，ヘリカルコイル形の核融合実験装置に対するダイバータの設計に関連して直径9 mm以下の細管を用いて行われた限界熱流速の実験[(2)]，原子炉の圧力容器と炉心溶融物(デブリ)の凝固相の間の微小すきまにおける気液対向流制限(CCFL)特性を調べた実験[(3)]，小形熱交換器におけるマイクロチャネル内の沸騰気液二相流の薄膜挙動[(4)]と熱伝達[(5)(6)]や直径10 mm水平管内の純粋冷媒と混合冷媒の沸騰二相流の圧力損失と流動様式[(7)]，短い細管ノズルから高温水を噴出する際の自己蒸発による気液二相噴流特性[(8)]を調べた実験がある．さらには，宇宙環境での高性能冷却を目指した液体ヘリウム気液二相流の

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数値解析[9]ならびに潜熱利用ループ式排熱システムの動特性の実験と解析[10][11]，プレート式熱交換器内の垂直沸騰流動特性を中性子ラジオグラフィー法で調べた実験[12]，二相閉ループ熱サイフォンでノートパソコンのCPUを冷却しようとする実験[13]，蒸気圧を駆動源として高所の高温部から低所の低温部へ熱を輸送するトップヒート形の熱輸送ループの開発に関する実験[14]がある．

さらに複雑な断面形状をもつ原子炉燃料集合体内の沸騰二相流については，従来形の正方格子燃料体における限界出力[15]，新形のちゅう密三角格子燃料体における限界出力と圧力損失[16]~[18]を調べた実験がある．

以上より，小形熱交換器におけるマイクロチャネル等の微細管内の流れに関する研究，宇宙環境での高性能冷却を目指した研究，新形のちゅう密三角格子燃料体に関する研究が，最近の研究動向であるように思われる．

3. 熱移動を伴わない気液二相流動系

原子炉燃料集合体内の二相流についてまず述べる．新形のちゅう密三角格子燃料体に関するものが多く，圧力損失の実験[19]，スペーサが環状流の液膜挙動に及ぼす影響を調べた数値解析[20]，サブチャネル間の乱流混合を調べた実験[21]がある．そのほか，正方格子燃料体における中央サブチャネルと壁面サブチャネルのボイド率と圧力損失の評価法を調べた研究[22]，管群を横切る気泡流の流動特性をPIV法で調べた実験[23]，スペーサが環状流の液膜挙動に及ぼす影響を調べるために円管内に模擬スペーサを入れた実験がある[24][25]．さらに，原子炉の循環系への応用を目指した，鉛ビスマス中の気泡ポンプ[26]やジェットポンプ[27][28]の実験的研究もある．原子炉とは直接のかかわりはないが，気液二相流用のポンプとして，遠心ポンプ[29]や二重反転形軸流ポンプ[30]の実験的研究も行われている．

二相流の気液分離については，沸騰水形原子炉用の旋回羽根を使う遠心分離形[31]と壁面のぬれ性を低下させたY継手を使う方法[32]がそれぞれ実験的に研究されている．さらに継手などの特異点(singularity)での流れについては，急拡大部におけるボイド率と流動様式の変化[33][34]や急縮小部におけるボイドの振動や抗力低減法[35][36]を実験的に調べたものがある．

マイクロチャネル内の二相流の研究には液体の微細化[37]や二酸化炭素などの排気ガスの吸収[38][39]を目的としたものがあり，マイクロバブルの研究には抗力低減現象の解明[40][41]を目的としたものがある．

気液二相流の数値解析に用いられる二流体モデルやドリフトフラックスモデルの改良に資するための研究も多く見られた．レーザフォーカス変位計を用いたマイクロチャネル内の液膜計測[42]と通常口径管内の環状流の液膜構造の計測[43][44]，液膜界面積濃度の軸方向発達特性[45]を調べた研究が行われた．さらには，狭あい流路における気液界面波特性に及ぼす流路姿勢の影響[46]や5 mm管内垂直上昇環状流において流動障害物が液滴の液膜への付着に及ぼす影響[47]を調べた研究，流動様式遷移のモデル化にかかわる研究[48]，微小重力下を対象とするドリフトフラックスモデルの開発研究[49]も行われた．

気液二相流の数値解析は非常に進歩しており，気液界面における局所的現象や多次元的挙動の計算が行われるようになってきている．すなわち，液体金属中の微細気泡群が収縮によって圧力波の伝ぱを減衰する過程を解いたもの[50]，三次元One-way気泡追跡法によって垂直円管内の未発達の気泡流とスラグ流を解いたもの[51][52]，格子ボルツマン法によって水平矩形流路内の層状流の界面成長を解いたもの[53]，Phase-fieldモデルに基づく新たな計算法によって気泡内の圧力上昇や静止した気体中や液膜上への単一液滴の落下過程を解いたものがある[54][55]．

4. 気液の混合系

本展望では，プール沸騰や貯水槽内のエアレーションのような片方の相のみが流動する系を気液の混合系と称している．この系については，2004年1月～2006年8月までの日本機械学会発行の論文集に35件の研究が発表された．ここでは，それらのなかで最近増えている研究について触れる．

静止液中のさまざまな条件下における単一気泡の挙動を扱った実験や数値解析が7件［例えば，文献(56)］，同じく二つの気泡の相互干渉を扱ったものが5件［例えば，文献(57)］，気泡の生成過程を扱ったものが3件あった［例えば，文献(58)］．これらは，気泡が群として液とともに流動する気泡流の流動現象の解明に資するためのものと思われる．

波立った水面［例えば，文献(59)］あるいは静止液中に発生したマイクロバブル[60]から二酸化炭素，二酸化窒素や空気を水(海水を含む)に溶解させる研究も6件あった．これらは地球温暖化物質の水中溶解による大気中の濃度低下，あるいは酸素を水中に供給して好気性バクテリアを活性化させ水質浄化，に役立てようとする研究であり，今後も盛んに行われると思われる．また，マイクロバブル等の微細気泡の生成過程・

発生法・抗力低減作用に関する研究も4件あった［例えば，文献(61)］．マイクロバブル技術は，上述の水質浄化のほか洗浄，化学反応促進，超音波造影法などの医療分野への応用が実用化されつつあり(62)，それぞれの作用を説明しうるメカニズムの学術的な解明は十分とはいえないものもあるが，新たな応用分野の開拓を目指した研究者や技術者は年々加速的に増えている．したがって，マイクロバブル技術にかかわる研究もますます盛んになると予想される．

なお，上記の引用文献以外にも優れた論文は多数あったが引用文件数が多くなりすぎるので割愛させていただいた．他意はないのでご容赦願いたい．

5. おわりに

2004年1月～2006年8月までに，「日本機械学会論文集B編」と「JSME International Journal, Series II」に発表された気液二相流動系に関する55報を中心として研究のレビューを行い，併せて気液の混合系に関する35報の研究動向にも触れ，両分野での今後の研究課題を探った．その結果，現在までの2～3年間はコンパクトやマイクロをキーワードとする実験的研究や気泡の挙動に関する解析的研究が盛んであったことがわかり，それらにかかわる研究は今後も当分は続けられるように感ぜられた．本展望は，気液二相流にかかわる研究者・技術者が今後の研究課題を考えられる際の参考になれば幸いである．

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