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OpenSTREAM
An Open-Source Platform for Two-Phase Flow Modeling and Simulation

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ABSTRACT

The OpenSTREAM computational environment is a new open-source platform designed to facilitate efficient and collaborative development and validation of one-dimensional, multi-field, two-phase flow simulation models across research institutions. It includes several simulation frameworks: a mixture model, a two-fluid model, a three-field model, and an advanced four-field model of annular two-phase flow. The current implementation supports single-component, thermally expandable, steady-state, and transient boiling two-phase flows in single straight channels under reasonable simplifying assumptions. The two-fluid model solves a six-equation system governing mass, momentum, and energy conservation for each phase, capturing hydrodynamic and thermal non-equilibrium effects. The three-field model follows a classical framework (vapor, drops and film) for annular two-phase flow, while the advanced four-field model explicitly represents both the base liquid film and dispersed disturbance waves as separate fields. In all solvers, field interactions and wall closure models have been implemented either from well validated models from the literature or from simple considerations, providing a foundation for future collaborative improvements. Simulations of a representative boiling

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water two-phase flow case using all simulation frameworks show consistent and reasonable predictions. A comparison with the TRACE system code demonstrates that the implemented two-fluid solver produces reliable and consistent results. Finaly, the validation exercises from the original four-field model development are reproduced. OpenSTREAM, along with its validation and application database, will soon be publicly available on dedicated GitHub repositories under the permissive MIT license.

KEYWORDS

Two-phase flow, boiling, multi-field, annular flow, open-source.

1. INTRODUCTION

One-dimensional, two-phase flow simulation models are generally well documented in the literature. These models typically rely on averaging methods, as described in [1], along with necessary closure models that are often developed and validated within specific validation ranges. However, the implementation of these models is usually restricted to complex proprietary computational codes, such as system and subchannel analysis codes widely used in the nuclear industry. While these codes enable the simulation of entire reactor systems from normal operation up to design basis accident (including three-dimensional effects in the reactor core), their complexity and restricted access tend to hinder the development, performance evaluation, and validation of fundamental closure models.

To promote two-phase flow research and improve the development of one-dimensional simulation models for steady-state and transient conditions, the OpenSTREAM computational environment (**Open S**olvers for **T**wo-phase flow **R**esearch, **E**ngineering **A**nalysis and **M**odeling) has been developed and recently introduced in [2][3][4]. This modern open-source platform is designed to facilitate efficient and collaborative research in two-phase flow modeling, including heat transfer and phase change phenomena. OpenSTREAM provides access to generic simulation frameworks and closure models while providing a flexible platform for future developments and enhancements. The current implementation supports single-component, thermally expandable, steady-state and transient boiling two-phase flows. The primary focus of the code being specifically intended for basic model development and validation, the geometry is currently limited to straight multi-wall channels. This covers most experimental setups used for two-phase flow model development and validation, such as tubes, annuli, rectangular channels, and small rod bundles with no significant 3-D effects.

OpenSTREAM includes several two-phase flow simulation frameworks: a simple mixture model, a simplified non-equilibrium two-fluid model, as well as a three-field and an advanced four-field model of annular two-phase flow (currently limited to thermal equilibrium conditions). The open-source implementation of the recently developed four-field model of annular two-phase flow [5], which explicitly accounts for both base film and disturbance waves, was the primary driver for the code development. However, OpenSTREAM has evolved into a much more comprehensive and flexible two-phase flow simulation platform. By supporting a growing effort toward open-source code development for nuclear reactor analysis and other engineering fields [6], OpenSTREAM ensures transparency and accessibility, allowing researchers to scrutinize, modify, and extend the code capabilities. This open approach not only fosters collaboration opportunities but also enhances trust in the results obtained by these simulation frameworks.

2. SIMULATION FRAMEWORKS

The OpenSTREAM computational environment is developed using the MATLAB programming language, following a modern object-oriented architecture. The implemented simulation frameworks focus on one-dimensional, thermally expandable, boiling two-phase flow in channels, capturing both hydrodynamic and thermal non-equilibrium effects relevant to system code applications in the nuclear industry. Any straight channel can be defined with constant cross-sectional area, including local obstructions. Multiple independent walls can be specified, allowing for simulations in tubes, annuli, rectangular channels, and small rod bundles with non-uniform heating rates. Phase fluid properties are computed using the CoolProp library [7]. Any steady-state or transient boundary conditions are supported, including the definition of any arbitrary axial power distributions.

Currently, OpenSTREAM offers the following two-phase flow simulation frameworks:

- **Mixture** – Simple and generic three-equation model.
- **Two-fluid** – Generic six-equation model typical of system codes.
- **Three-field** – Annular two-phase flow model accounting for vapor, drop, and liquid film fields.
- **Four-field** – Advanced annular two-phase flow model explicitly accounting for disturbance waves.

The two-fluid model allows for thermal non-equilibrium (e.g., subcooled boiling and post-CHF conditions), while the annular two-phase flow models are currently limited to thermal-equilibrium (i.e., applicable up to film dryout). Additional simplifications across all simulation frameworks include neglecting surface tension forces, heating due to friction, temporal pressure gradients, and spatial saturated fluid enthalpy gradients. These simplifications are justified under high-pressure conditions and for any conceivable operational transient relevant of Light Water Reactor (LWR) core operation [5][8].

2.1. Mixture simulation framework

The mixture simulation framework implemented in OpenSTREAM is based on a simple three-equation model. Using the mixture mass flow rate, W, as primitive variable, the time-dependent mass conservation equation is written as:

$$\frac{\partial}{\partial t}\left(\frac{W}{u}\right)+\frac{\partial W}{\partial z}=0 \tag{1}$$

where u is the mixture velocity. The time-dependent momentum conservation equation, solved for the pressure p, is given by:

$$\rho A\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial z}\right)=-A\left(\frac{\partial p}{\partial z}+\frac{\partial p_K}{\partial z}+\cos\theta\, g\rho\right)-\Pi_p\tau_{wall} \tag{2}$$

where ρ is the mixture density, A is the coolant cross-section area, Π_p is the wall perimeter, θ is the channel inclination angle, g is the gravitational acceleration, τ_{wall} is the wall shear stress and K denotes any local obstruction. Finally, using the mixture enthalpy, h, as primary variable, the time-dependent energy conservation equation is expressed as:

$$\rho A\left(\frac{\partial h}{\partial t}+u\frac{\partial h}{\partial z}\right)=\sum \Pi_p^n q''^n_{wall} \tag{3}$$

where q''_{wall} is the wall heat flux and the superscript n refers to the wall index.

In this framework, non-equilibrium thermal effects can be accounted for by using constitutive relations (e.g., subcooled boiling models), and phase velocity slip can be included using slip or drift flux void models. Various wall friction and singular pressure loss models for both single-phase and two-phase flows are implemented in OpenSTREAM, and users can easily add new closure models.

The mixture solver is executed before any other simulation framework, providing a robust initialization state. To address the ill-posed nature of multi-field conservation equation systems caused by pressure-velocity coupling, the pressure gradient solution from the mixture model is directly applied across all simulation frameworks without further consideration. While this simplification significantly improves numerical stability, it limits the applications to sufficiently coupled two-phase flows (characteristic of high pressure LWR applications, including annular two-phase flow) and introduces minor inconsistencies in the conservation equations.

2.2. Two-fluid simulation framework

The two-fluid simulation framework implemented in OpenSTREAM, documented in [9], is based on a generic six-equation model [1] derived under reasonable simplifying assumptions. It is intended to be nearly equivalent to two-fluid simulation frameworks used in most nuclear reactor system codes, such as TRACE [10], limited to single straight channels.

The two-fluid model is widely used in engineering applications to simulate two-phase flow, allowing for hydrodynamic and thermal non-equilibrium conditions. The approach uses the concept of interpenetrating continua, where two distinct phases (e.g., a liquid and its vapor) coexist and interact dynamically through mass, momentum and energy exchanges, including heat transfer and phase change. The Euler averaging of local, instantaneous, phase conservation equations require the interfacial exchange terms to be captured via closure relations. Although a complete two-fluid model can be complex, simplifying assumptions can be made without significant loss of accuracy, depending on the applications.

Using the liquid, W_l, and vapor, W_v, mass flow rates as primitive variables, the time-dependent mass conservation equations are expressed as:

$$\frac{\partial}{\partial t}\left(\frac{W_l}{u_l}\right)+\frac{\partial W_l}{\partial z}=-A\cdot a_i\cdot(\Gamma-\Lambda)-\sum\Pi_p^n\Gamma_{wb}^n \tag{4}$$

and

$$\frac{\partial}{\partial t}\left(\frac{W_v}{u_v}\right)+\frac{\partial W_v}{\partial z}=Aa_i(\Gamma-\Lambda)+\sum\Pi_p^n\Gamma_{wb}^n \tag{5}$$

where u_l and u_v are the phase velocities, Γ and Λ are the interfacial evaporation and condensation mass fluxes, a_i is the volumetric interfacial area and Γ_{wb} is the vapor generation mass flux due to wall boiling. The time-dependent momentum conservation equations, solved for the phase velocities, are given by:

$$\rho_l A_l\left(\frac{\partial u_l}{\partial t}+u_l\frac{\partial u_l}{\partial z}\right)=-Aa_i\Lambda(u_l-u_v)-A_l\left(\frac{\partial p}{\partial z}+\cos\theta\, g\rho_l\right)+Aa_i\tau_{v,l}-\Pi_p\tau_{wall,l} \tag{6}$$

and

$$\rho_v A_v\left(\frac{\partial u_v}{\partial t}+u_v\frac{\partial u_v}{\partial z}\right)=\left(Aa_i\Gamma+\Pi_p\Gamma_{wb}\right)(u_l-u_v)-A_v\left(\frac{\partial p}{\partial z}+\cos\theta\, g\rho_v\right)-Aa_i\tau_{v,l}-\Pi_p\tau_{wall,v} \tag{7}$$

where ρ_l and ρ_v are the phase densities, A_l and A_v are the phase cross-section areas, $\tau_{wall,l}$ and $\tau_{wall,v}$ are the phase wall shear stresses and $\tau_{v,l}$ is the interfacial shear stress. Finally, using the liquid, h_l, and vapor, h_v, enthalpies as primary variables and considering that any phase change is associated with bulk phase enthalpy, the time-dependent energy conservation equations are written as:

$$\rho_l A_l \left(\frac{\partial h_l}{\partial t} + u_l \frac{\partial h_l}{\partial z}\right) = -Aa_i(h_l - h_v)\Lambda + \sum \Pi_p^n \left(q"^n_{wall,l} - (h_v - h_l)\Gamma^n_{wb}\right) \quad (8)$$

and

$$\rho_v A_v \left(\frac{\partial h_v}{\partial t} + u_v \frac{\partial h_v}{\partial z}\right) = Aa_i(h_l - h_v)\Gamma + \sum \Pi_p^n q"^n_{wall,v} \quad (9)$$

where $q''_{wall,l}$ and $q''_{wall,v}$ are the wall heat fluxes to the liquid and vapor phases, respectively.

Simple interfacial and wall closure models have been implemented, subject to future improvements. Within a generic two-fluid simulation framework, such models involve (1) interfacial topology and volumetric interfacial area, (2) interfacial transfer fluxes, and (3) wall transfer terms and thermal transitions, such as Critical Heat Flux (CHF). In the current state of development, basic two-phase flow regimes and corresponding interfacial length scales, interfacial/wall transfer terms, and transitions have been implemented (Walter, 2024).

2.3. Three-field simulation framework

The three-field simulation framework implemented in OpenSTREAM is based on a nine-equation model specifically simplified for annular two-phase flow simulation up to liquid film dryout (i.e., under thermal equilibrium assumption), solving the coupled mass and momentum conservation equations for the liquid film and droplet fields (the vapor solution is obtained from the mixture solver). Such models are commonly used for advanced Boiling Water Reactor (BWR) fuel thermal-hydraulic simulations, applied to subchannel analysis such as in the Westinghouse MEFISTO-T code [8][11]. This framework explicitly represents three distinct flow fields: vapor, entrained droplets and liquid film, as shown in Figure 1.

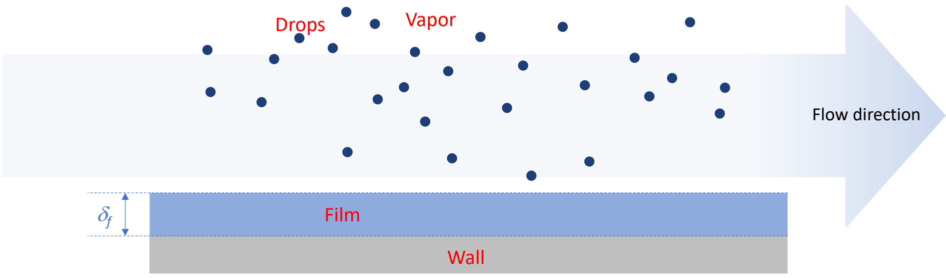


Figure 1. Field geometrical characteristics in three-field simulation framework (vapor, drops & film)

Using the liquid film mass flow rate, W_f, as primitive variable, the time-dependent mass conservation equation is written as:

$$\frac{\partial}{\partial t}\left(\frac{W_f^n}{u_f^n}\right) + \frac{\partial W_f^n}{\partial z} = \Pi_p^n (D - E^n - \Gamma^n_{wb}) \quad (10)$$

where u_f is the film velocity, D is the drop deposition mass flux, E is the film entrainment mass flux, and n refers to the wall index (applicable to multi-wall geometries, e.g., an annulus with different heating rate). Under the considered saturated assumptions, the drop mass flow rate, W_d, can be simply computed by subtracting W_f from the total liquid mass flow rate obtained from the mixture model. The time-dependent momentum conservation equations, solved for the film and drop velocities, are given by:

$$\rho_{ls}\delta_f^n\left(\frac{\partial u_f^n}{\partial t}+u_f^n\frac{\partial u_f^n}{\partial z}\right)=\left(u_d-u_f^n\right)D-\delta_f^n\left(\frac{\partial p}{\partial z}+\cos\theta\, g\rho_{ls}\right)+\left(\tau_{v,f}^n-\tau_{wall,f}^n\right) \tag{11}$$

and

$$\rho_{ls}\left(\frac{\partial u_d}{\partial t}+u_d\frac{\partial u_d}{\partial z}\right)=\left(\sum \Pi_p^n\left(u_f^n-u_d\right)E^n\right)\frac{\rho_{ls}u_d}{W_d}-\left(\frac{\partial p}{\partial z}+\cos\theta\, g\rho_{ls}\right)+\frac{A_d}{V_d}\tau_{v,d} \tag{12}$$

where u_d is the drop velocity, δ_f is the film thickness, $\tau_{v,f}$ is the vapor/film interfacial shear stress, $\tau_{wall,f}$ is the wall shear stress on the liquid film, $\tau_{v,d}$ is the vapor/drop interfacial stress, A_d and V_d are the drop interfacial area and volume (based on surface averaging), and subscript s stands for saturated properties. Alternatively, the field velocities in OpenSTREAM can be calculated using simple algebraic relations. Finally, under thermal equilibrium assumption, the film energy conservation equation simplifies to the following rate of film evaporation:

$$\Gamma_{wb}^n=\frac{q''^n_{wall}}{h_{vs}-h_{ls}} \tag{13}$$

The closure models for this framework includes drop deposition, film entrainment, interfacial transfer fluxes, wall transfer terms, drop size and onset of annular two-phase flow criteria. Several well-established correlations have been implemented in OpenSTREAM (see examples in Section 3.1), with full flexibility for users to introduce additional models.

2.4. Advanced four-field simulation framework

The four-field simulation framework implemented in OpenSTREAM extends the three-field model by separating the liquid film into a slower continuous base liquid film and faster dispersed disturbance waves, solving the coupled mass and momentum conservation equations for the base liquid film, disturbance waves and droplet fields. This recently developed model [5] provides a more detailed representation of annular two-phase flow dynamics by explicitly modeling the intermittency of disturbance waves and their impact on mass and momentum transfers.

In this framework, disturbance waves are modeled as dispersed fluid particles, characterized by fundamental macroscopic parameters such as the wave shape factor (amplitude-to-width ratio) and the wave number density (spatial wave frequency). The four distinct flow fields: vapor, entrained droplets, base liquid film and disturbance waves, are illustrated in Figure 2. Further schematics detailing all considered mass and momentum transfer terms can be found in [5].

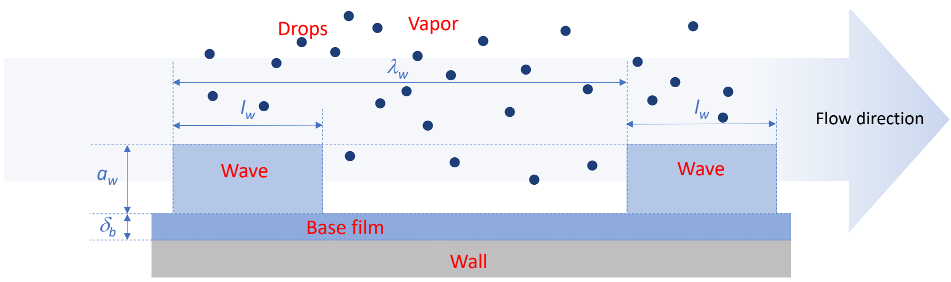


Figure 2. Field geometrical characteristics in four-field simulation framework (vapor, drops base film & disturbance waves)

Using the base film, W_b, and wave, W_w, mass flow rate as primitive variables, the time-dependent mass conservation equations are written as:

$$\frac{\partial}{\partial t}\left(\frac{W_b^n}{u_b^n}\right)+\frac{\partial W_b^n}{\partial z}=\Pi_p^n\left(D_b^n-\Gamma_{wb,b}^n+\Psi_w^n-\Psi_b^n\right) \tag{14}$$

and

$$\frac{\partial}{\partial t}\left(\frac{W_w^n}{u_w^n}\right)+\frac{\partial W_w^n}{\partial z}=\Pi_p^n\left(D_w^n-E^n-\Gamma_{wb,w}^n-\Psi_w^n+\Psi_b^n\right) \tag{15}$$

where u_b and u_w are the base film and wave velocities, D_b and D_w are the field drop deposition mass fluxes, $\Gamma_{wb,b}$ and $\Gamma_{wb,w}$ are the field evaporation mass fluxes due to wall boiling, and Ψ_w and Ψ_b are the mass exchange fluxes between base film and waves (including turbulent mixing effects). The film entrainment only applies to the waves, consistent with experimental observations [5]. The drop mass flow rate, W_d, is calculated using the same method as in Section 2.3. The time-dependent momentum conservation equations, solved for the base film and wave velocities, are given by:

$$\rho_{ls}\delta_b^n\left(\frac{\partial u_b^n}{\partial t}+u_b^n\frac{\partial u_b^n}{\partial z}\right)=D_b^n(u_d-u_b^n)+\Psi_w^n(u_w^n-u_b^n)-\delta_b^n\left(\frac{\partial p}{\partial z}+g\rho_{ls}\right)+\beta_b^n\tau_{v,b}^n+(1-\beta_b^n)\tau_{w,b}^n-\tau_{wall,b}^n \tag{16}$$

and

$$\rho_{ls}\delta_w^n\left(\frac{\partial u_w^n}{\partial t}+u_w^n\frac{\partial u_w^n}{\partial z}\right)=D_w^n(u_d-u_w^n)+\Psi_b^n(u_b^n-u_w^n)-\delta_w^n\left(\frac{\partial p}{\partial z}+g\rho_{ls}\right)+(1-\beta_b^n)\left(\tau_{v,w}^n-\tau_{w,b}^n\right) \tag{17}$$

where β_b is the base film interfacial fraction [5], $\tau_{v,b}$ is the vapor/base film interfacial stress, $\tau_{w,b}$ is the wave/base film interfacial stress, $\tau_{v,w}$ is the vapor/wave interfacial stress and $\tau_{wall,b}$ is the wall shear stress on the base film. To improve numerical stability, the base film gravitational pressure and buoyancy terms can be neglected. Finally, under thermal equilibrium assumption, the field energy conservation equations simplify to the following rates of base film and wave evaporation:

$$\Gamma_{wb,b}^n=\frac{q''^n_{wall,b}}{h_{vs}-h_{ls}} \tag{18}$$

and

$$\Gamma_{wb,w}^n=\frac{q''^n_{wall,w}{}^n}{h_{vs}-h_{ls}} \tag{19}$$

where $q''_{wall,b}$ and $q''_{wall,w}$ are the wall heat fluxes to the base film and disturbance waves, respectively.

Additionally, the four-field framework includes a Boltzmann transport equation of wave number density [5] to model hydrodynamic non-equilibrium effects related to wave formation, merging, splitting, and dissipation, that are characteristic of developing annular two-phase flows (due to, e.g., inlet effect, phase change, geometrical change or transient). Using a relaxation time approximation, this is expressed as:

$$\frac{\partial N_w^n}{\partial t}+\frac{\partial}{\partial z}(u_w^n N_w^n)=\frac{N_w^{eq,n}-N_w^n}{t_w^{Relax}} \tag{20}$$

where N_w is the wave number density, superscript eq refers to the equilibrium state, and t_w^{Relax} is the relaxation time, typically set to values below 1 second based on experimental data [5]. This equation is analogous to the bubble number density transport equation used in bubbly flow modeling [12].

The closure models implemented in the four-field simulation framework extend those used in the three-field model by incorporating additional terms representative of (1) wave/base film and wave/vapor mass and momentum transfers, and (2) equilibrium wave number density and associated relaxation time. The default closure models in OpenSTREAM are consistent with the original derivation of the four-field model [5], but users can modify or extend these models as needed.

2.5. Numerical resolution

The OpenSTREAM computational environment follows a modern object-oriented architecture. The governing mass, momentum, and energy conservation equations are first-order advection equations with nonlinear source terms. These are solved using a simple first-order upwind scheme, which is sufficient for this purpose and consistent across all solvers.

Time integration is performed using a fully implicit backward Euler discretization. Nonlinear closure terms (such as film entrainment and drop deposition) and field couplings are handled using a fixed-point iteration method at each timestep until convergence is achieved. This approach ensures numerical stability without imposing any timestep restrictions, resulting in a robust solution algorithm.

The transient solvers are used for both steady-state and transient simulations. The steady-state solution is obtained by solving for a pseudo-transient with large time steps (e.g., 1 second) to rapidly reach convergence.

The solving algorithms are implemented as methods within each solver class definition, making them modular and easily replaceable with more advanced numerical algorithms in future updates.

3. RESULTS AND DISCUSSION

This section presents a demonstration of OpenSTREAM's current capabilities and validation of the two-fluid and four-field simulation frameworks. The main results can be reproduced by accessing the OpenSTREAM and OpenSTREAM-database repositories (project name: NURETH21), which will soon be publicly available on GitHub [13].

3.1. Demonstration case and comparison of simulation frameworks

To illustrate OpenSTREAM's capabilities, boiling water two-phase flow was simulated using all available simulation frameworks in a 3.5 m uniformly heated tube with an inner diameter of 8.8 mm. The pressure was set to 6 MPa, with a mass flow rate of 0.07 kg/s, a total power input of 87.5 kW and a slightly subcooled inlet (1.14 MJ/kg) corresponding to one of the CHF tests used in [14]. In the simulations, a 2 m adiabatic section was added downstream of the heated length to observe the predicted two-phase flow developments toward hydrodynamic and thermal equilibrium.

For each simulation framework, the closure models are selected as follows:

- **Mixture** – Models consistent with the homogeneous equilibrium assumption (that is, no subcooled model and a phase velocity ratio set to 1).
- **Two-fluid** – All models are documented in [9].
- **Three-field** – The onset of annular two-phase flow is calculated according to [15] and the entrainment and deposition mass fluxes are calculated using the models documented in [16].
- **Four-field** – Most closure models are consistent with [5] and t_w^{Relax} is set to 0.2 seconds.

Full momentum conservation equations were solved for all fields, except for the neglected gravitational pressure buoyancy forces acting on the base film, consistently with [5].

Figure 3 presents the axial distributions of input wall heat flux, as well as the liquid field mass flow rates and void fractions predicted by all simulation frameworks. The results from the three- and four-field models are displayed from the onset of annular two-phase flow (at 0.77 m). Due to the thermal equilibrium assumption, the (total) liquid and vapor mass flow rates remain unchanged for the mixture, three-field, and four-field models.

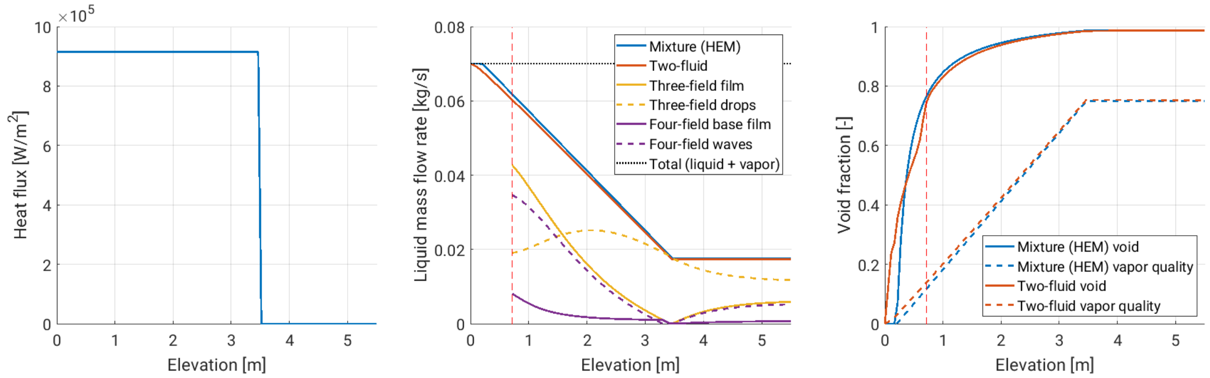


Figure 3. Axial distributions of input wall heat flux (left), predicted liquid field mass flow rates (center) and void fractions (right) for all available simulation frameworks.

As expected, wall boiling initiates near the inlet up to the end of the heated section (at 3.5 m). The two-fluid model effectively captures thermal-non-equilibrium effects between the phases in the subcooled region, resulting from an imbalance between wall boiling and interfacial condensation. The three-field model captures the development of the liquid film and drops along the annular flow region, progressing toward near-complete film dryout at the end of the heated length (consistent with the CHF test conditions). The four-field model provides additional details by capturing the mass transport of base film and disturbance waves, showing that waves carry most of the liquid mass, consistent with experimental observations [5]. In the adiabatic section downstream of the near-complete film dryout, the system returns towards equilibrium, with liquid mass redistributing toward the film.

Figure 4 shows the axial distributions of other key liquid film parameters predicted by the three-field framework (film thickness and velocity) and the four-field framework (base film thickness, wave amplitude, field velocities, and wave frequency). The wave velocity is significantly higher than the base film velocity, and the wave amplitude decreases sharply along the heated length. The film behavior (from the three-field model) yields an intermediated behavior, as expected. The drop velocity is slightly lower than the steam velocity due to interfacial drag and the exchange of fast depositing droplets and slow entrained film.

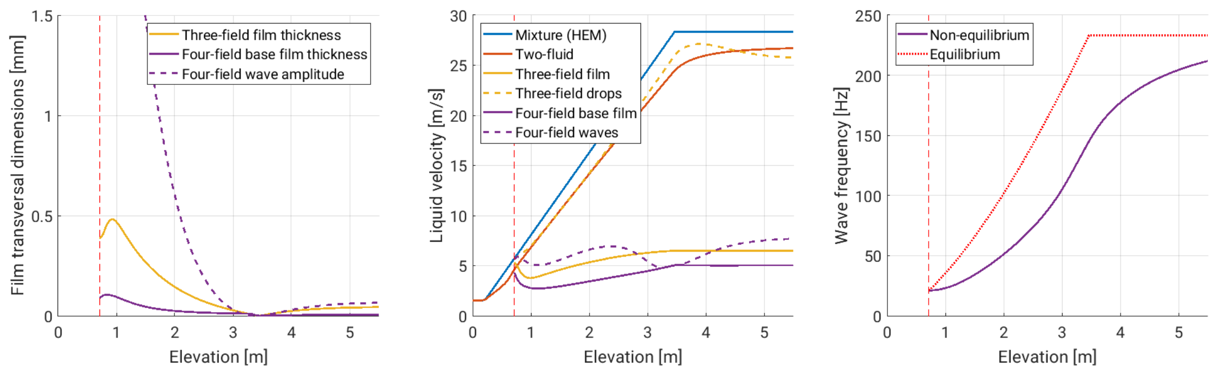


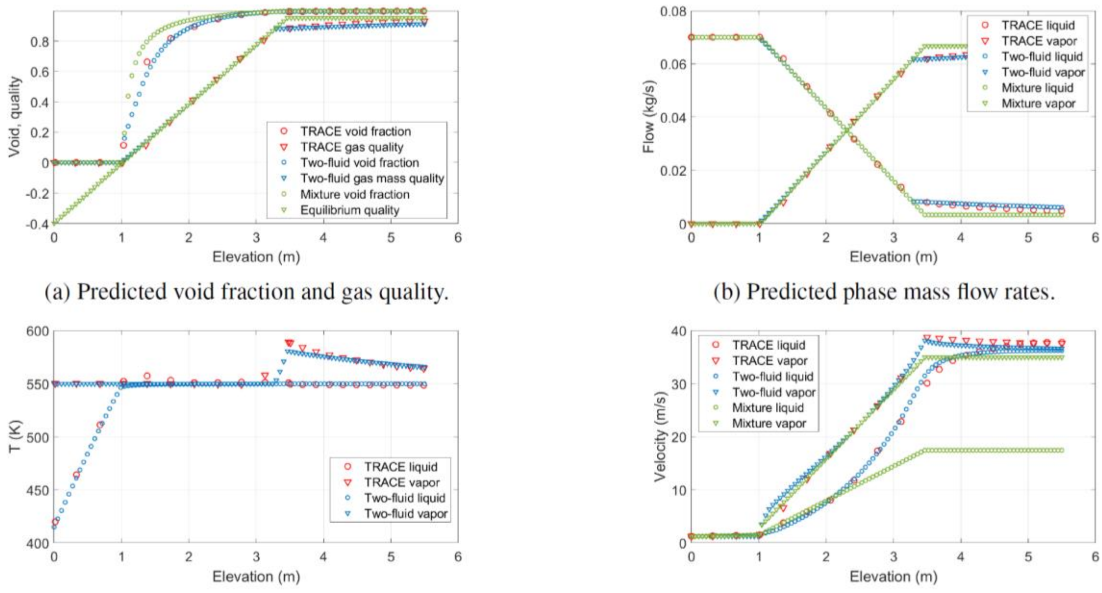
Figure 4. Axial distributions of predicted film thickness / wave amplitude (left), field velocities (center) and wave frequency (right) for the three and four-field simulation frameworks.

Interestingly, the disturbance waves decelerate near dryout, due to reduced interfacial drag, and merge with the base film (i.e., Equations (16) and (17) become equivalent for low wave amplitudes). In addition, the wave number density transport equation successfully captures the non-equilibrium development of wave frequency. Using a realistic relaxation time of 0.2 seconds [5], the wave frequency can hence be significantly different from the hydrodynamic equilibrium state (i.e., as predicted by an algebraic equation) in developing annular two-phase flow.

3.2. Two-fluid solver comparison against TRACE code

To demonstrate the capabilities of the two-fluid solver, a boiling water two-phase flow case was simulated using the same test geometry and conditions as in Section 3.1, except for a significantly lower inlet enthalpy (0.6 MJ/kg) and a higher total power input (150 kW) leading to post-CHF conditions. Simulation results from the OpenSTREAM mixture (with a phase velocity slip ratio of 2) and two-fluid models were compared against the TRACE code [10]. To ensure consistency, the subcooled boiling model was turned off in both OpenSTREAM and TRACE simulations. The details of the calculations and selected closure models can be found in [9].

Figure 5 compares the axial distributions of key phase variables. The two-fluid model successfully captures saturated boiling from 1 m to 3.25 m (where CHF is predicted). In the post-CHF region, the wall heat flux to the vapor phase results in thermal non-equilibrium conditions, with superheated vapor and saturated liquid (Figure 1c). The resulting temperature gradient across the phases drives interfacial evaporation (Figure 1a and Figure 1b) which persists downstream the end of heated length, along with interfacial momentum transfers from the faster vapor to the slower liquid, towards hydrodynamic (Figure 1d) and thermal equilibrium.



(a) Predicted void fraction and gas quality.

(b) Predicted phase mass flow rates.

(c) Predicted phase temperatures.

(d) Predicted phase velocities.

Figure 5. Axial distributions of phase variables predicted by TRACE (red), OpenSTREAM mixture model (green) and two-fluid model (blue).

The two-fluid model implemented in OpenSTREAM agrees well with the results from TRACE, demonstrating its reliability for steady-state simulations. However, the current model's applicability to complex transient scenarios remains limited due to the current simplifying assumptions regarding flow regimes and interfacial topology transitions, as discussed in [9].

3.3. Four-field model validation

The four-field model of annular two-phase flow was developed and validated in [5]. To ensure consistency between the original model implementation (in the Westinghouse MEFISTO-T code [17]) and the OpenSTREAM implementation, the same validation process was repeated, consisting of:

- Validation of closure models under fully developed annular two-phase flow.
- Validation of non-equilibrium hydrodynamic processes in developing annular two-phase flow.

3.3.1. Fully developed annular two-phase flow validation

The experimental dataset from [18] provides steady-state annular two-phase flow measurements for steam/water at pressure from 3 to 9 MPa, mass fluxes from 500 to 2000 kg/m^2/s, and equilibrium thermodynamic qualities from 0.2 to 0.7 in a pipe (20 mm diameter) and annulus (17/26 mm inner/outer diameter), hence relevant of BWR core operation. Measurements were taken at the outlet of a long (8 to 9 m) adiabatic test section, ensuring fully developed annular two-phase flow.

Figure 6 compares OpenSTREAM predictions of base film thicknesses, wave velocities, and wave number densities against experimental data. The results are satisfactory and nearly identical to those presented in [5], demonstrating successful validation. A few outliers can be observed (in particular, the single wave number density measurement at high mass flux), that may be due to experimental variability and uncertainties.

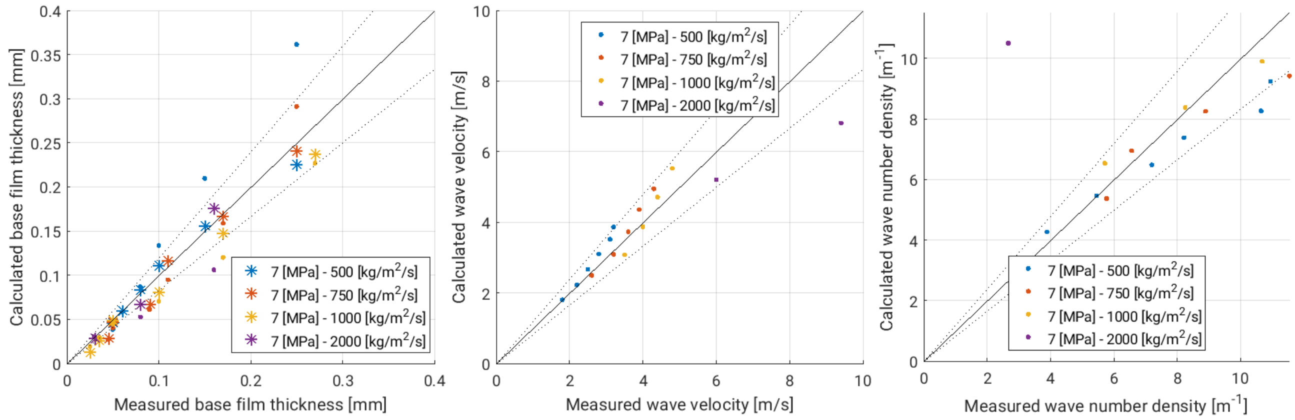


Figure 6. Predicted vs measured base film thickness (left), wave velocity (center) and wave number density (right) in steam/water at the outlet of a long adiabatic channel.

3.3.2. Developing annular two-phase flow

The spatial relaxation of disturbance wave characteristics downstream of a heated section of boiling steam/water two-phase flow was experimentally investigated in [19] for a vertical, uniformly heated 800 mm pipe (4 mm inner diameter) at 2.95 MPa. Wave characteristics were measured within an adiabatic section at 140, 452 or 848 mm downstream the heated region, capturing the recovery process of disturbance wave properties toward equilibrium.

A time relaxation, t_w^{Relax}, for the wave number density transport equation of 0.2 seconds was found to best match the data [5]. Figure 7 compares OpenSTREAM simulations of wave velocity and wave time period distributions against selected measurements. The results closely match the experimental trends and are fully consistent with those presented in [5], in both heated and adiabatic regions.

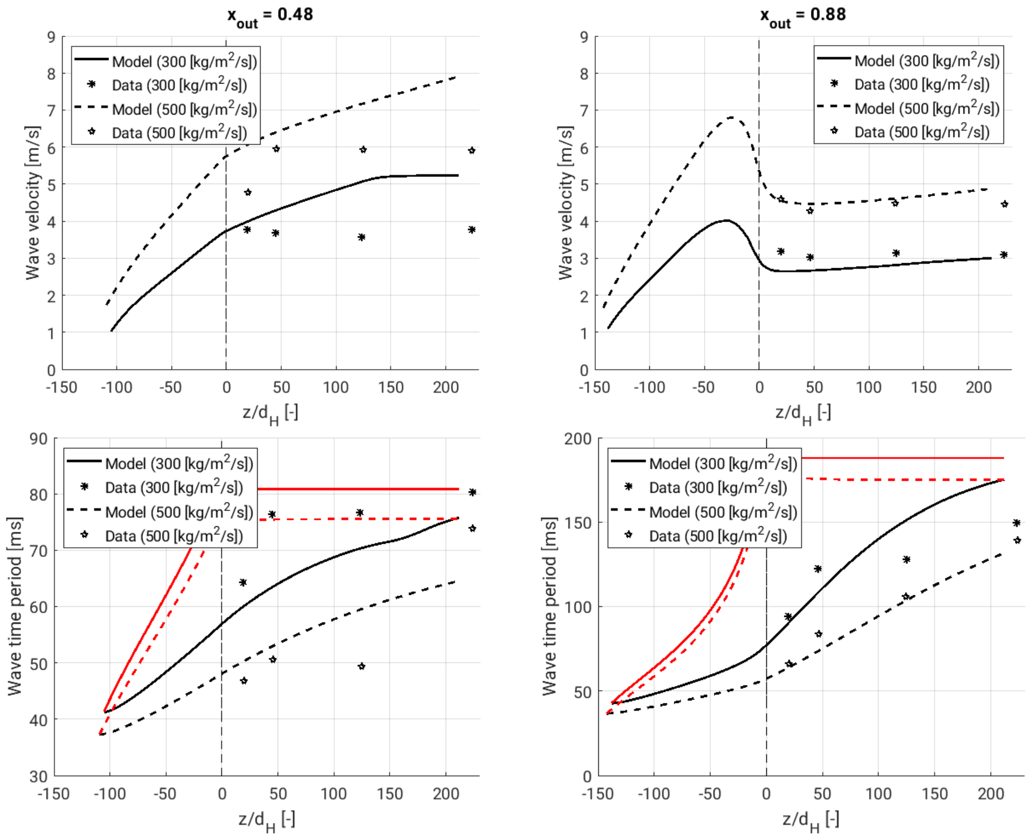


Figure 7. Measured and predicted axial distributions of wave velocity (top) and wave time period (bottom, including calculated equilibrium in red) in steam/water along a channel ($z/d_H < 0$ heated and $z/d_H > 0$ adiabatic).

4. CONCLUSIONS AND OUTLOOK

A new, modern open-source computational environment for one-dimensional, multi-field, two-phase flow simulations in straight channels has been presented. OpenSTREAM includes mixture, two-fluid and three-field simulation frameworks, along with an advanced four-field model of annular two-phase flow. All frameworks demonstrated consistent and reasonable results for the presented boiling water steady-state case. This platform is designed to facilitate access to such two-phase flow simulation frameworks, supporting collaborative model development, performance evaluation, and validation across research institutions.

A simplified two-fluid model was derived and implemented, designed to be nearly equivalent to nuclear reactor system codes for single-channel applications. This framework solves a system of six conservation equations, complemented by interfacial and wall closure relations that depend on flow regimes and wall heat transfer transitions. The model effectively captures hydrodynamic and thermal non-equilibrium effects between phases. For the presented steady-state case, which included a post-

CHF non-equilibrium region, the two-fluid solver provided reasonable results, showing strong agreement with the TRACE code.

The implemented three- and four-field models of annular two-phase flow provide state-of-the-art frameworks for advanced simulations. While the three-field model has been successfully applied in nuclear fuel thermal-hydraulic analysis for years (e.g., in [8][11][20]), the recently developed four-field model [5][17] offers enhanced capabilities to simulate hydrodynamic and thermal phenomena related to the intermittent transport of disturbance waves over the liquid film. These frameworks solve field mass, momentum, and energy conservation equations under the assumption of thermal equilibrium, supplemented with closure relations for wall and interfacial transfer processes. The models successfully predict the transport of liquid fields (entrained droplets, base film, and disturbance wave), including phase change and relevant non-equilibrium hydrodynamic phenomena in both steady-state and transient conditions. The four-field model was shown to yield equivalent validation results to its original derivation and implementation. In addition, an early application of the three-field model implemented in OpenSTREAM to BWR fuel rod bundles is documented in [21].

Future collaborative enhancements to OpenSTREAM are expected, including the development of advanced closure models, volumetric interfacial area transport, wall condensation, interfacial thermal relaxation models, wall heat transfer models, and pressure-velocity coupling. Support for multi-component fluids and non-condensable gases, thermal non-equilibrium three and four-field models (for post-dryout applications), wall thermal models, and further explorations of intermittent base film dryout between disturbance waves (as observed in [22][1]) are also anticipated. Additional improvements may focus on more computationally efficient numerical solvers, support for non-uniform channel cross-sections and addressing the neglected terms in the momentum and energy conservation equations (depending on application needs). Furthermore, the implementation of OpenSTREAM in more accessible programming languages, such as Python or Julia, could be considered.

The main simulation results presented in this paper can be reproduced by accessing the OpenSTREAM and OpenSTREAM-database repositories (project name: NURETH21), which will soon be publicly available on GitHub [13] under the permissive MIT license, following the completion of documentation and user guides.

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