SYLVIA - a software to study ventilation network, fire, and airborne contamination

Jean-Paul Joret[1*], and *William* Plumecocq[1]

[1]IRSN/PSN-RES/SA2I/LIE, CE Cadarache - Bat 702 - BP 3, 3115 Saint Paul-lez-Durance, France

Abstract. SYLVIA is a mature software package developed by IRSN used internally by IRSN to carry out fire safety studies. SYLVIA is currently the only software available which seamlessly couples using an implicit method the operation of a complete ventilation network and the effects of one or more fires in the premises of this network. Outside IRSN, this software is mainly used to simulate the operation of ventilation networks in existing installations in order to study incidental scenarios or interventions. The aim of this paper is to present the SYLVIA software and its objectives. It covers ventilation network modelling, fire modelling, and heat and mass exchange modelling. From the user's point of view, a description of the scenario options and the GUIs available is also given. Finally, an application example based on a validation case is presented.

1 The SYLVIA software

The SYLVIA software [1] is designed to predict the behaviour of mechanical and natural ventilation, fire spreading, the propagation of hot gases and smoke, and the transfer of airborne contaminants within mechanically ventilated enclosures in normal or degraded situations. Indeed, it is a simulation tool to compute the consequences of multi-compartment fires in industrial or nuclear facilities, which are equipped with a ventilation network, which includes ducts, room leaks, dampers, fans, horizontal/vertical openings, filters, and more.

The Institut de Radioprotection et de Sûreté Nucléaire (IRSN) began developing the SYLVIA software in 2004, based on experience gained from coupling the two IRSN software packages: SIMEVENT for ventilation and FLAMME-S for fire. The first version, released in 2006, integrates the various models of these two software packages.

The SYLVIA software is designed:
- to enhance the functionality of existing ventilation networks, by forecasting the outcomes of any interventions on the network, including expansion, reduction, or decommissioning of an existing facility,
- to carry out safety studies: sensibility analysis, expert systems [2],
- to verify design decisions in ventilation network and fire safety,
- to aid in the design of ventilation networks: recent activity at the limits of the use of the SYLVIA software.

The SYLVIA software can perform both transient calculations and steady state calculations on ventilation networks.

The SYLVIA software is coded in C++ and its Graphical User Interfaces are coded in JAVA. It is compatible with both Windows and Linux operating systems.

2 Modelling

2.1 Ventilation network

The design of ventilation network relies on a graph formed of nodes connected by branches.

A node represents either a room within the ventilation network or a boundary condition. A room is represented by one or two Lagrangian control volumes where the physical quantities, such as pressure, temperature, density, and particle or gas species concentration and mass fraction are all assumed to be uniform at any given time. The conservation equations for mass, species, and enthalpy model the state of a room and its control volumes at each instant. The mixture of gases constituting the atmosphere obeys the law of perfect gases.

A branch within the network represents either a passive component, such as pipe, filter, damper, leak, valve, or opening, or a driving component, such as fan, or controller. Several branches can be connected to each control volume in the room. A uniform mass flow rate is assumed in branches and is a function of the pressure difference at its boundaries and the aeraulic resistance. The generalised Bernoulli equation models the state of a branch (excluding openings) at each instant is. The mass flow rate through an opening is driven by the density difference at its boundaries [3].

* Corresponding author: jean-paul.joret@irsn.fr

The modelling of a branch's aeraulic resistance depends on its type. This resistance can be evaluated by using data obtained on-site and provided by the user, such as pressures of the nodes at the branch terminal and volumetric flow rate. Alternatively, the resistance can be determined by the user or calculated based on the branch's geometry, rugosity, and Reynolds number.

Branch's outgoing flow is distributed to the receiver node, depending on its number of control volumes and on the model used. The entire flow can be added to the volume located at the branch's height, or split based on the densities of flow and volumes, with or without heat exchange.

A controller is a component that can control a variable, such as pressure or flow rate, based on a user-set setpoint value. This is achieved through adjusting a control parameter, such as aeraulic resistance, opening angle, or speed rotation, within a branch of the system. Two control modes are available in SYLVIA: ideal control, which minimises the difference between the setpoint and the measurement instantly; and PID (Proportional, Integral, Derivative) control, which replicates a controller's real behaviour.

2.2 Species

The SYLVIA software is capable of handling multiple gaseous species which are described by their physical properties such as molar mass or temperature-dependent functions like enthalpy, thermal conductivity, viscosity, and emissivity. It is noteworthy that these properties remain unaffected by pressure as the SYLVIA scenarios are formulated for a small range of pressure variation; variations in the properties as a function of pressure are overlooked.

Additionally, the software can manage multiple type of particles, either solid (airborne contaminants) or liquid (water spray droplets) distributed among any number of size classes.

Combustible species are species including properties relative to fire.

A multitude of chemical reactions can be modelled in a room, such as combustion reactions or Arrhenius law-controlled chemical transformations. In a chemical reaction, the stochiometric coefficients for each species remain constant.

A set of common species is released with the SYLVIA software.

2.3 Fire

The fire design is based on the widely recognized two-zone fire modelling [4,5]. This software describes each room where a fire occurs using two Lagrangian control volumes, with a lower and an upper gas layer separated by a thermal interface that evolves with time. To achieve an accurate simulation of fire and its effects, walls must be described around the room.

The SYLVIA software's fire modelling features numerous sub-models that include fire source, plume, mirror effect, scale effect, combustion, radiative heat transfer, and horizontal/vertical hot smoke propagation. The software models usual fire sources, such as gas burner, pool fire, wall fire, and prescribed mass loss rate, and complex fuels in fire engineering applications, like electrical cabinets (with open or closed doors), cable trays, and glove boxes.

Fire heat release rate may be limited due to oxygen depletion (Peatross and Beyler law [6], Lower Oxygen Limit law [7]) in the fire compartment until the possible fire extinction based on oxygen concentration, surfacic mass loss rate criterion [5], adiabatic flame temperature criterion [8,9] or simply by lack of fuel. To mitigate fire sources or collect soot, models simulating water spray systems can be used.

As the heat conduction can be calculated by a 1D approach in walls and targets, the ignition of fire source becomes possible by means of a target temperature criterion.

2.4 Heat and mass exchanges

The convective, conductive, and radiative heat transfers within the rooms, and radiative and convective heat transfers in the pipes of the ventilation network are fully modelled and play a major role for predicting gas temperature and pressure, particularly in proximity to a fire.

Particle deposition models [10] and vapour condensation models [11] can be activated in the ventilation network. Sedimentation [12], Brownian diffusion [13], and thermophoresis [14] are considered in the deposition models within pipes and rooms. Impaction models [15,16] for horizontal and vertical pipe bends are also available.

Filter clogging models [17] are also available to evaluate the time evolution of the aeraulic resistance of a filter when solid particles are carried by the gas flow. The filter clogging is evaluated through the evolution of the deposited particles' cake thickness in the filter pleats, which notably affects filter aeraulic resistance.

2.5 Scenario options

The user has access to a wide range of scenario options.

Mass or energy injection models are available. The former can be used to simulate inerting, whereas the latter can be used to simulate heating elements. These can be used to accurately reproduce an operating or incident scenario.

Moreover, the behaviour of various elements in the ventilation network can be altered under certain conditions, such as fan stop or start, controller setpoint, opening or closing of valves or doors, or starting of a fire. These activation conditions are expressed as logical statements that may refer to variables computed by the software.

2.6 Numerical aspects

The SYLVIA software computes the thermodynamic states of the ventilation network over time by solving a set of ODEs (Ordinary Differential Equations). To calculate the ODE system, a numerical algorithm employing a first order BDF (Backward Differential Formula) method is implemented, which is an implicit and multistep technique, ideal for stiffness problems [18].

The linear system is solved using an iterative Newton-Raphson algorithm. The pressure of each room, gas temperature, and mass fractions in each volume, mass flow rate in each branch, interface height for rooms with two volumes, temperature in wall meshes and targets, and regulation parameter for controllers are the unknown variables of the system.

The time step is managed automatically according to both the previous time step and the maximum number of iterations required for convergence on the previous time step. In addition, the maximum increase of an unknown during a time step can be defined by the user.

3 Graphical User Interfaces

The SYLVIA software comes with several user-friendly and specific GUIs. These include:
- a pre-processing tool to facilitate data entry and control, access to documentation, and of course software execution,
- post-processing tools for plotting calculation results or replay a calculation,
- external applications such as a calculation launcher, or applications for evaluating aeraulic resistance, checking calculation results, or adjusting a ventilation network, etc.

4 Validation

To assess the capability of SYLVIA software for simulating properly fire scenarios and ventilation network, a Verification and Validation process is applied, based on about 370 test cases including 220 public test cases.

5 Application example

This is a validation case of the filter clogging model using the SYLVIA software in comparison with experimental data. The test has been carried out in the calorimetric hood of the SATURNE facility at IRSN in Cadarache as part of the acceptance of renovation work on the ventilation network at the GALAXIE platform in 2017. The test uses six CAMFIL HEPA filters (reference 1560.08.10) to collect soot from a 1 m² Hydrogenated Tetra-Propylene (HTP, i.e., $C_{12}H_{26}$) pool fire.

In the SYLVIA model used to simulate this experiment, the ventilation network replicates the experimental system. It includes a large air intake connected to the volume containing the fireplace through a non-return valve, followed by the filtration system and then fans responsible for extracting the air to the chimney. Information on the filters come from the data provided by CAMFIL filters' manufacturer.

The soot particles produced by the HTP pool fire are presumed to be spherical. The particle size distribution is replicated by a lognormal distribution, with a count median diameter of 0.23 µm and a standard deviation of 2.3. The fuel mass loss rate and the gas temperature evolution in the duct upstream of the filters are injected to prevent any estimation errors that may impact the outcomes of the clogging model.

The clogging model is validated through a comparison of the pressure difference time profile across the filter and the clogging factor, which is the ratio of the resistance value to its initial value.

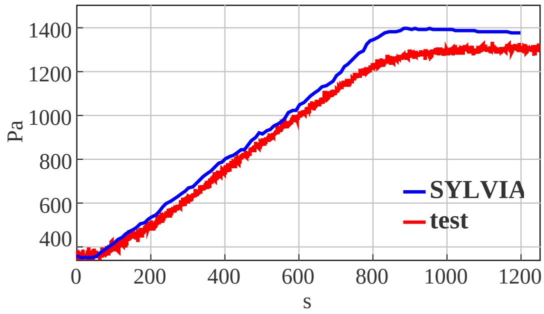

Fig. 1. Time evolution of the pressure difference at the filter

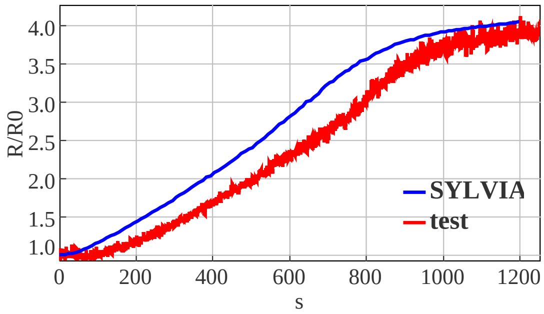

Fig. 2. Time evolution of the clogging factor

The SYLVIA software accurately replicates the pressure difference across the filter and its progression. With regards to the clogging factor, the SYLVIA software anticipates to a certain extent the changes in filter resistance. This issue can be attributed to the fact that the clogging model does not consider the fractal dimension of soot particles.

6 Conclusion

The SYLVIA software is a mature tool that has been developed for several years by IRSN. Its primary objective is to predict the behaviour of ventilation networks in normal or degraded situations, even in the presence of fire. It implements state-of-the-art physical models and comes with specific graphical user interfaces and complete documentation.
With almost 20 years of development, SYLVIA is a proven solution that has yet to be presented to the scientific community.

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