Validation of a Network Fire Model Using the Ex-Shadwell Submarine Ventilation Doctrine Tests

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ABSTRACT

There is a need for fire modeling tools capable of rapid simulation of fire growth and smoke spread with complex ventilation in multiple compartments. Currently available tools are not capable of either the speed, the simulation of complex ventilation arrangements, and/or the ability to participate as a federate in a simulation environment. To address this, a new fire model was developed called FSSIM (Fire and Smoke SIMulator) [1]. FSSIM is a network model whose core thermal hydraulic routines are based on MELCOR [2]. FSSIM capabilities include remote ignition, multi-layer heat conduction, radiation streaming, HVAC systems, detection, suppression, oxygen and fuel limited combustion, and simple control systems. FSSIM was used to simulate four tests from the ex-*Shadwell* Submarine Ventilation Doctrine Tests. Excellent results are obtained in predicting the time-dependent temperature, visibility, and velocities.

KEYWORDS: modeling, validation, HVAC

INTRODUCTION

A new fire model has been developed for simulating fire growth and smoke spread onboard naval vessels. The core physics models are not naval specific; therefore, the model is also applicable to simulating any multiple compartment enclosure. This paper will provide a brief overview of the model's physics and algorithms. This overview will be followed by model validation using fire test data from the US Navy's fire test platform, the ex-*USS Shadwell* [3].

MOTIVATION

The impetus for developing a network fire model arose from current needs of the design process for future surface combatants [4]. Fire represents a significant threat to a ship both in terms of its impact on crew health and equipment. Fire growth and spread onboard a combatant can quickly result in crew casualties and a loss of mission capability. Furthermore, the presence of flammable liquids, missile propellants, and explosives onboard a combatant greatly increases the risk represented by a fire.

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As part of the design process for future combatants, candidate designs must demonstrate that they meet specific requirements for maintaining fighting capability after a weapon hit. This is done by simulating the total ship response to hundreds or thousands of scenarios. The simulation process encompasses the timeline from weapon detonation through cascading damage from fire and flooding and ending with the damage control response of automated systems and ship's crew. Since the design process is continuous, analysis needs to be rapid so that any lessons learned can be meaningfully integrated into the evolving design.

Currently available computational tools do not support this process. Computational fluid dynamics (CFD), while quite capable in simulating the effects of fire, do not support rapid analysis in a cost effective manner. Heuristic methods, rules or correlation based methods, while rapid, are overly conservative in their fire spread predictions. Existing zone models and other lumped parameter methods, while rapid, lack the ability to model control systems, have limitations in the complexity of ventilation systems, and were not designed for integration as a federate in a simulation environment. This last requirement is paramount, as the fire and smoke spread simulation must operate interactively with other simulation tools to create a true virtual ship simulation. In order to meet the needs of the design process, the decision was made to develop a new fire model. To maximize speed, a network model approach was used.

FIRE AND SMOKE SIMULATOR (FSSIM)

FSSIM [1] is written in standard Fortran 95. It has been successfully compiled and executed on both Windows and Linux platforms and has operated as a command line program, as a DLL with a C++ wrapper, and as a model federate over a TCP/IP socket using a Tcl/Tk wrapper.

FSSIM has the following capabilities: 1D flow model including friction losses and temperature-dependent specific heat; 1D multiple-layer, temperature-dependent conduction heat transfer; N-surface, gray-gas radiation heat transfer, including radiation streaming through openings; bidirectional flow through horizontal (hatches) and vertical (doors) flow connections; surface flow leakage; combustion product species tracking; oxygen- and fuel-limited combustion; multiple user-defined fires along with fire spread via compartment-to-compartment heat transfer; HVAC systems including ducts, dampers, and fans with forward and reverse flow losses and multiple fan models; fire detection; remote ignition; fire suppression; fire spread prevention via boundary cooling; simple control systems to link operation of equipment to computed parameters; fast, near realtime execution speed; ability to incorporate time-dependent changes in compartment volume (flooding); and ability to execute interactively with a simulation master as part of a model federation.

The overall FSSIM solver is based on the MELCOR [2] thermal hydraulic solver. MELCOR is a nuclear power plant, containment safety-analysis package containing a number of submodels including heat and mass transfer, spray cooling systems, deflagrations, and molten core-concrete interactions. FSSIM also includes a radiation heat transfer model based on CFAST's model [5] and a 1D finite difference heat conduction model similar to that found in HEATING [6]. Due to space limitations, this paper will only briefly discuss the primary algorithms for heat and mass transfer. A more detailed description can be found in [7].

Hydraulic Model

The FSSIM hydraulic solver solves the nodal conservation equations for mass, momentum, and energy and uses the ideal gas law equation of state. Energy and mass are conserved explicitly using an explicit Euler scheme; whereas, momentum is conserved for semi-implicitly. Energy conservation and mass conservation use a control-volume approach, a single compartment or a ventilation system node. Momentum is implicitly solved for over all vent connections and HVAC components using an iterative solver. The FSSIM HVAC model assumes no mass or energy storage in an HVAC system. Since mass and energy are explicit and momentum implicit, momentum may not be absolutely conserved. However, the flow fields in a lumped-parameter model are highly abstracted with many contributors to momentum are not being captured; thus absolute conservation is not really possible in a physical sense. It is critical, however, to fully account for toxic combustion products and the energy release from combustion.

In general, donor (upwind) quantities are used. The exception is the density term in the momentum equation, where an iteration dependent density formulation is used. If net pressure force across a junction is small, a change in flow direction may occur while iterating the solver. This would result in a change in the donor density, which could result in further flow oscillation. To prevent this, as the iteration count increases, the density value transitions from upwind to the prior timestep value.

In the momentum equation the velocity at the next timestep is determined by the pressure and pressure gradient within the compartment at the next timestep. This is a function of the mass and energy flows in and out of the compartment, which itself depends on the flows in all hydraulically connected compartments. Thus, junction velocity is a function of the pressures in all of the compartments directly connected to the junction’s endpoints by other flow connections. The result is a system of linear equations for each junction, duct segment, and duct node (required for mass conservation in ducts).

FSSIM computes bidirectional flow in both vertical and horizontal flow connections by treating each junction internally as two parallel junctions. For a doorway, the junction is partitioned according to the location of the neutral plane at the start of each timestep. For a horizontal junction, the method of Cooper is used [8].

Steps are taken to make the solution process more efficient. First, FSSIM determines if distinct hydraulic regions exist. If so, each region is solved separately. Second, if any flow connection has a zero area during a timestep, perhaps due to progressive flooding, it is removed from the matrix prior to solution. Third, compartments are generally directly connected to only a small number of other compartments; therefore, the matrix is sparse. Sparse LU decomposition is performed to solve for the velocities.

Heat Transfer

FSSIM includes submodels for correlation-based convection heat transfer, including correlations for plumes in large volume spaces; N-surface, gray-gas, radiation heat transfer; and 1D, multi-layer, temperature-dependent conduction. A compartment can have as many surfaces as required to define its heat conduction paths. For example, if a compartment adjacent to three compartments along one wall, three surfaces can be defined for that wall.

Conduction

Conduction heat transfer in FSSIM is based on multi-layer, temperature dependent, 1D heat transfer in Cartesian coordinates. In FSSIM only conductivity, k, and specific heat, c, are allowed to vary with temperature. The general equation is discretized with central differences in space and a Crank-Nicholson scheme in time. It is solved using a tridiagonal solver. The 1D surface is divided into a series of nodes with properties defined at node centers and temperatures at node faces.

Noding in FSSIM is determined automatically. For each material a maximum surface node size is determined using a lumped capacity Biot number criterion. If the material thickness is less than this maximum value, a lumped parameter approach is used. Otherwise, the surface is noded by setting the outer nodes to the maximum size and then successively doubling the node size into the surface. This is the approach recommended by GOTHIC, which is a computational tool for reactor containment safety analysis [9].

Radiation Heat Transfer

FSSIM uses an N-surface, gray-gas radiation heat transfer solver based on the solver implemented in CFAST [10]. The solver was modified to allow for streaming through large openings. Radiation absorption is computed using the ABSORB routine from CFAST [5]. For surfaces that are defined as being transparent to radiation the surface emissivity is set to 1, and the surface radiation source term is set to the incoming radiation on the backside of the surface. This results in coupling the radiation solutions of one or more compartments. To avoid construction of a single solution matrix accounting for all surfaces in the joined compartments, those compartments with transparent surfaces are iterated up to five times to obtain a converged solution.

The radiation matrix is dense; however, a typical compartment has a small number of surfaces. LU decomposition is used to solve for the net radiative flux. To further reduce the computational burden of the radiation solver, a compartment is bypassed if it has no transparent surface, no pyrolysis, and its surface and gas temperatures are within 2 K of each other and less than 310 K. The temperature criterion results in a maximum radiation heat transfer error of 10 W/m^2. If the velocity solver iterates, only compartments with combustion or transparent surfaces are solved again.

Combustion

As part of the FSSIM input, users can define fires to start at explicit times and users may also choose to allow fire to spread. Ignition of additional fires is determined at the beginning of each timestep based on the compartments “usetype”, which denotes a fuel loading and fuel classification. Separate ignition criteria can be defined for surfaces, incoming vent flows, or the compartments internal temperature [11]. Overhead surfaces can be given a different ignition temperature from non-overhead surfaces.

Pyrolysis is determined by one of three methods: constant pyrolysis rate, a t^2 pyrolysis rate, or a user-defined time vs. pyrolysis rate table. Growth in pyrolysis can be limited by specifying a maximum pyrolysis rate in kg/m^2-s. All fires can be given an end time in either absolute time or fuel loading. The calculated pyrolysis rate can be reduced by various mechanisms including suppression and oxygen availability.

Combustion product species are generated based on user-provided yields for each usetype. Currently, unburned fuel is tracked as a species, but no separate model has been implemented to burn it in downwind compartments.

Solution Algorithm

The FSSIM solver consists of a timestep initialization, an outer loop, and an inner loop. The outer loop monitors the overall convergence of the timestep and limits the maximum relative change in thermophysical conditions over a timestep. The inner loop handles the solution of the velocity and those parameters required for the velocity computations.

The outer loop monitors the overall convergence of the timestep solution and computes the final predicted values of updated quantities. It begins by estimating the compartment specific heats for the end of the current timestep using the current heat and mass transfer solution. The inner loop is then executed. Upon return from the inner loop a series of stability criteria are checked that limit the maximum change in mass, pressure, and temperature. If these criteria are exceeded the time step is reduced and the outer loop iterated. If the solution is successful, a new timestep size is determined based on the most limiting stability criterion.

The inner loop contains the bulk of the computations for FSSIM. It begins by setting donor quantities. Suppression systems are updated and predictions are made for heat transfer and combustion. If a compartment is underventilated, combustion will be limited to the incoming oxygen with a relaxation on the maximum changes in heat release rate between iterations. Since pressure and velocity are tightly coupled and since the heat release as a momentum source is strongly dependant on inflowing air, the relaxation reduces oscillations in heat release rate. With all momentum source terms updated, the momentum solution matrix is constructed and solved. This is followed by updating the end of timestep quantities. If any junction velocity changes sign or magnitude by a user-definable criterion, the inner loop is repeated. Heat release rates are recomputed only in underventilated compartments. If the maximum number of inner iterations is exceeded, the timestep is reduced by 50 % and the outer loop is cycled.

EX-*USS SHADWELL* 688 SUB TEST SERIES

Test Description

During 1995 and 1996 a series of tests were conducted in a modified portion of the port wing wall of the ex-*USS Shadwell* (LSD-15) [3]. The port wing wall was modified to represent the forward section of a Los Angeles (SSN 688) class attack submarine. In total, 108 tests were performed within the test area to evaluate the existing doctrine and tactics under prototypical fire conditions and to evaluate alternative approaches to maintaining tenability of key spaces [12]. The submarine test area is depicted in Fig. 1 as plan views of each deck.

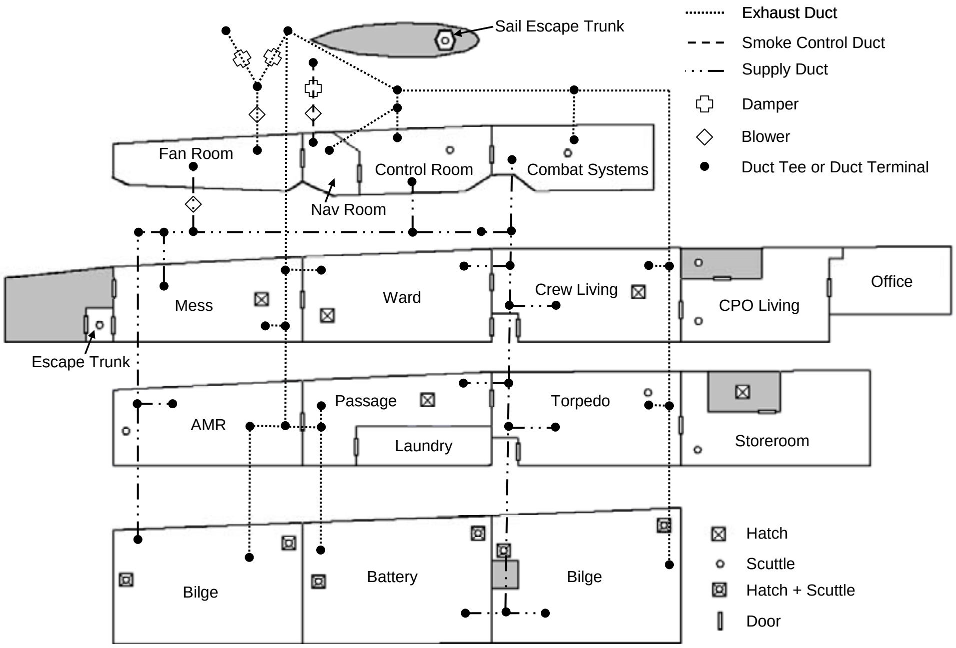

Fig. 1. Ex-*Shadwell* submarine test area (plan view) and HVAC system connectivity (shaded compartments are dead air volumes).

The test area contained twenty-three compartments and encompassed over 1000 m^3 of free air volume. The compartments were connected by fourteen hatches and scuttles, eleven doorways, three ventilation systems, four port frame bay openings and four starboard frame bay openings. The frame bay openings were vertical ducts connecting the laundry room to the control room (two starboard), passage to the control room (two port), and torpedo room to the combat systems space (two port and two starboard) that simulate the floating decks of a submarine, i.e. not affixed to the hull. Note the frame bay ducts are not shown in the test area figure. Most of the 108 tests had diesel pool fires which were placed in a variety of locations in the test area, the majority of them in the laundry room. Fire size, location, ventilation conditions, and, for some tests, manned response were varied. Approximately 360 channels of data were collected for each test, including selected hatch, duct, and doorway velocities; gas and surface temperatures; species concentrations; and visibility.

The ventilation systems were a supply system, an exhaust system, and a smoke control system with a combined total of three fans, three dampers, and 48 distinct segments of ducting. There were three modes of operation for the ventilation system: recirculation with the supply system taking suction from the fan room and discharging to the test area and the exhaust system doing the reverse, a surface ventilation mode where the exhaust was realigned to take suction from above the sail (weather), and an emergency ventilation mode where the supply and exhaust systems were secured and the smoke control system took suction from the navigation room and discharged above the sail (weather). The last two modes required opening an external hatch to serve as discharge in the surface ventilation mode and an intake in the emergency ventilation mode.

FSSIM Input Files

FSSIM was used to model the first 20 minutes of tests 3-10, 4-2, 5-3, and 5-14, which were all a 250 kW diesel fire in the laundry room. In all the tests ventilation operated for 1 minute in recirculation mode and was then secured. Test 3-10 had the frame bays closed, the escape trunk hatch to the ambient open, the laundry room door open, and the remaining doors either closed watertight or closed with a fabricated insert containing a 0.5 m x 0.15 m opening. Test 4-2 had the frame bays closed, all internal doors open, and no external hatches open. Tests 5-3 and 5-14 repeated test 3-10 with the frame bays opened. Test 5-14 also activated the smoke control system after 1 minute. For the remainder of this paper the tests will be referred to as follows: test 3-10 as the base case, test 4-2 as the closed boat case, test 5-3 as the frame bay case, and test 5-14 as the smoke control case. These test cases span the range of ventilation used during the test series. Other fire locations were not selected since only fires in the laundry room had mass loss measurements made of the pool fire. Volumes, wall surface and thicknesses, flow connections, and HVAC properties (duct sizes, flow losses, and fan curves) were provided in the form of a digital database representation of the submarine test area by Havlovick Engineering Services (HES). The fire for each test was specified based on weight loss measurements of the diesel fuel pan. Combustion products for the diesel fuel were based on measured CO and CO_2 ratios made in the laundry room and Koylu and Faeth's soot production correlation [13].

In total the FSSIM input file included 23 compartments, 20 doors and hatches, 56 HVAC ducts, 67 HVAC nodes, 3 fans, 3 dampers, and 171 heat transfer surfaces with seven steel thicknesses. All external boundaries of the test area were made airtight. All internal boundaries remained the original ex-Shadwell joiner bulkheads and were assigned leakage areas of 0.05 %. This resulted in an additional 65 flow connections. The simulation was performed on a Windows® 2000 PC with a 2 GHz AMD Athlon™ processor, and 20 minutes of simulation took 7 minutes of CPU time, a 3:1 simulation time to run time ratio. As an additional point of reference for computational speed, FSSIM was used to simulate an input geometry with approximately 2000 compartments, 3000 flow connections, and 12000 heat transfer surfaces on the same computer with a simulation time to run time ratio of 1:8.

Results

Since the tests simulated used the same fire source, a 0.68 m pan of medium weight diesel fuel, under varying ventilation conditions, the general time-dependent temperature rise in the test area was similar. Thus, measured vs. predicted temperatures over time, are only depicted for the base case, see Fig. 2. Temperature data consisted of one or two rakes of five to six thermocouples each in each test compartment. For comparison with the network model output, the average measured value and its spread are plotted. FSSIM temperature predictions are bounded by the measured values. Outside the laundry room, FSSIM temperature predictions closely track the average temperature. In the laundry room, the FSSIM temperature is above the average temperature; however, the thermocouple rake in the laundry room was distant from the fire and did not measure temperatures near the fire plume. The FSSIM compartment control volume includes the energy content of the plume. Given this, one would expect FSSIM to be higher than the average measured temperature (for example, if a 50 m^3 compartment had a TC rake measuring an average temperature of 100 °C away from a 1 m^3 flame volume at 1000 °C, the actual average would be 118 °C).

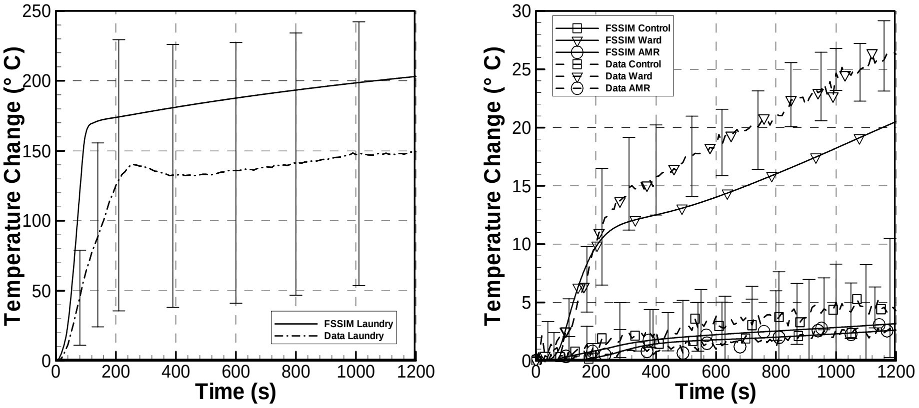

Fig. 2. Predicted and measured (with error bars show minimum and maximum) temperature change for the base case.

In each test, visibility measurements were made using a 1 m light path and a HeNe laser. Measurements were made in at multiple elevations; denoted as high, middle, or low; in eight compartments: combat systems, control room, CPO living, crew living, ward room, torpedo room, laundry passage (data not usable), and AMR. The next figure, Fig. 3, shows the measured vs. predicted light attenuation in the control room for the base case and the smoke control case. For both tests FSSIM is predicting well the visibility trend and magnitude and FSSIM is capturing the shift in visibility due to the smoke control system activation.

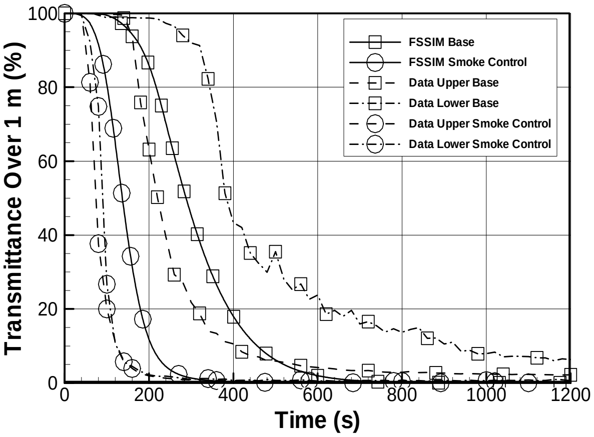

Fig. 3. Visibility in the control room for the base case and the smoke control case.

In the next four figures, Fig. 4 through Fig. 7, the temperature conditions at 20 minutes and the time to reach 50 % transmittance are depicted for each of the three tests. An N/A for transmittance indicates that the value of 50 % was not reached within 20 minutes. For all four cases FSSIM predictions reasonably match the data on all three decks in compartments with and without direct vent connections to the fire room. A comparison of Fig. 4 to Fig. 5 shows that FSSIM is correctly predicting the increased temperatures resulting from the closed boat as well as the increased extent of poor visibility due to the open doors. A comparison of Fig. 4 to Fig. 6 shows that FSSIM is predicting the shift in temperature and visibility that results from the opening of the frame bays. A comparison of Fig. 6 to Fig. 7 shows that FSSIM is properly predicting the change in vent flows, which result from the smoke control system activation as seen in the improved visibility conditions.

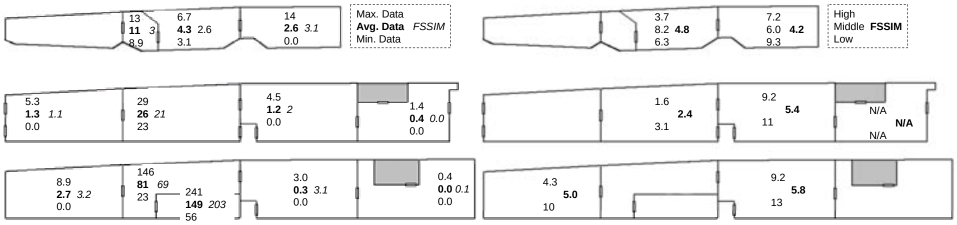

Fig. 4. Predicted and measured temperature change in °C at 20 minutes (left) and time in minutes to 50 % transmittance (right) for the base case.

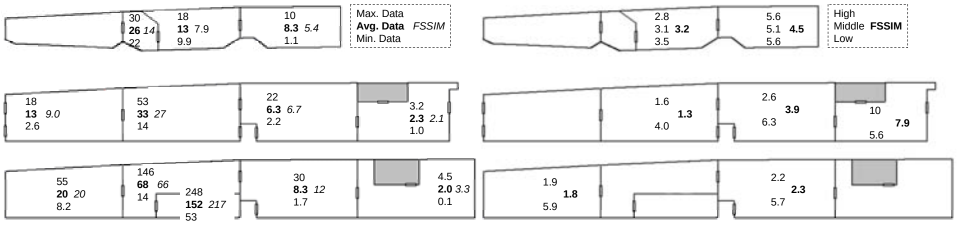

Fig. 5. Predicted and measured temperature change in °C at 20 minutes (left) and time in minutes to 50 % transmittance (right) for the closed boat case.

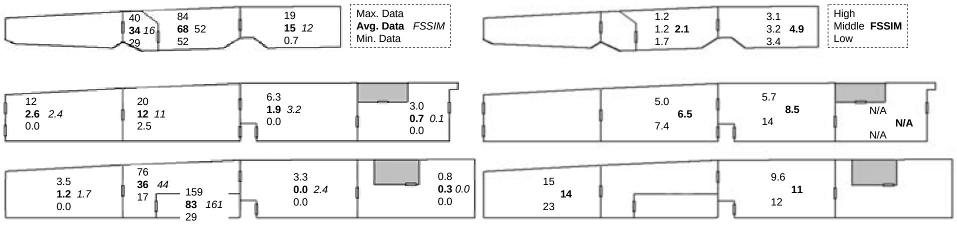

Fig. 6. Predicted and measured temperature change in °C at 20 minutes (left) and time in minutes to 50 % transmittance (right) for the frame bay case.

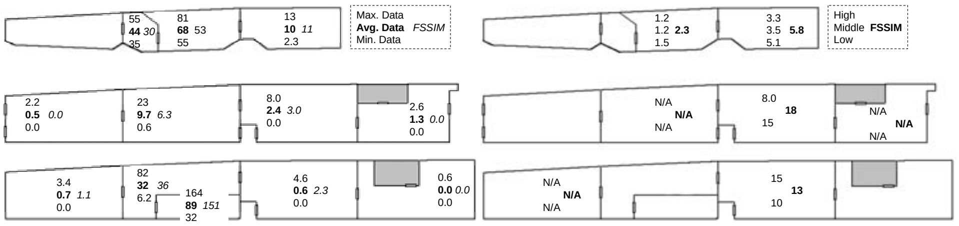

Fig. 7. Predicted and measured temperature change in °C at 20 minutes (left) and time in minutes to 50 % transmittance (right) for the smoke control case.

Of the three tests, only the smoke control test had velocity data that was useable for comparison purposes. In the figure below, Fig. 8, are velocities in the HVAC systems and in the frame bays. HVAC flows were computed based on fan curves and flow loss data provided by HES and blower inertia (the time to spin up or down the blow motor) was not accounted for. The three figures show excellent agreement of these quantities. This indicates that both the HVAC submodel is properly implemented, as seen in the ventilation duct predictions, and that buoyancy driven flows are being correctly predicted, as seen in the frame bay predictions. Note the later requires that the temperatures and pressures in the source and destination compartment be correct.

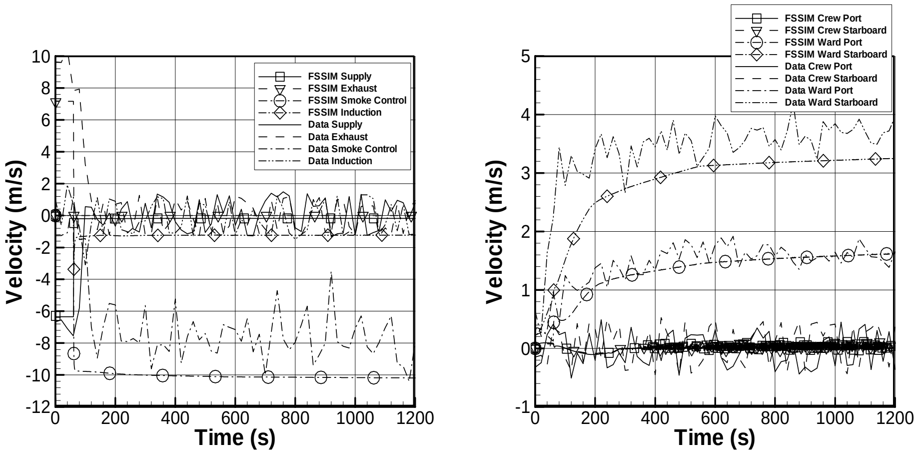

Fig. 8. Predicted and measured velocities in HVAC ducts (left) and frame bays (right).

The final comparison plot, Fig. 9, shows measured vs. predicted surface temperatures in the laundry room for the closed boat test. Unlike the gas temperature measurements, the measured surface temperatures consisted of a single surface mounted thermocouple for a given surface. Therefore, no surface averaged value exists to compare with the FSSIM prediction. Given this limitation of the data, the FSSIM predictions show a similar rate of rise in surface temperature and a similar magnitude change in surface temperature as seen in the data. This fact combined with the visibility and temperature predictions, indicates that FSSIM is properly apportioning energy between the surface and gas phase heat sinks.

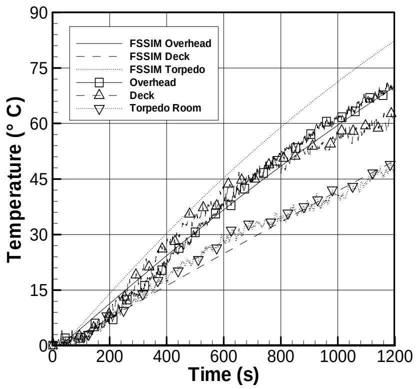

Fig. 9. Predicted and measured surface temperatures in the laundry room for the closed boat case.

CONCLUSION

A network fire model, FSSIM, was developed for the purpose of predicting fire growth and spread onboard naval combatants. The model was developed for fast execution, the ability to be run within a simulation environment as federate, and the capability to accommodate arbitrarily complex HVAC and compartment arrangements.

Comparisons of FSSIM predictions against data collected during the ex-*Shadwell* submarine tests show that FSSIM is capable of accurate, and rapid, predictions of the spread of heat and smoke over time from a fire inside of a multi-level set of compartments with complex ventilation. Temperatures, visibility, and HVAC system flows were all correctly predicted both near the fire, in the laundry room, and at locations remote from the fire. Furthermore, the predictions remained accurate through a range of natural and forced ventilation conditions within the test area including state changes of the forced ventilation systems.

The submarine test area contained multiple compartments on multiple levels with multiple HVAC systems. The overall complexity and layout of the test area is similar to that of a typical residential or commercial building with the exception that surfaces of land-based facilities are typically not steel. Given this, FSSIM could be used for these applications as well. FSSIM development and validation is still ongoing. However, the results shown here indicate FSSIM's potential as a new tool for general predictions of structure fires.

ACKNOWLEDGEMENTS

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