Recent Progress in Fire Simulations using NMF and Automatic Translation to IDA

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Abstract

The simulation of temperature and pressure development in the ventilation systems of an offshore oil platform during the initial phase of afire has been carried out using the IDA solver (IDA 1991). This paper focuses on the utility shaft and its ventilation system. The simulations are part of a project for the Norwegian oil company Statoil. That project is a total analysis of the situations in case of afire, with the objectives to decide the strategies of smoke control during the early stage of the fire. Different scenarios are analyzed and the simulation results are used together with lab measurements, CFD modelling, and experiences from real fires. The simulations are strongly aided by automatic translation from the Neutral Model Format (NMF) (Bring, Salhin and Sowell 1992) to IDA. The translator (NEUTRAN), which supports the current NMF definition, creates all the necessary FORTRAN code for IDA and also generates an input file. The connections among the components and the handling of the initial values are achieved by a simple system definition language. Some important effects that arise under a fire, such as stack effects and the effects caused by air expansion, are usually not modelled in a conventional air flow program. However, both have significant influence on pressure development in tall constructions and may cause undesired pressure differences during afire. The effects of air expansion cause a considerable pressure rise in the air enclosures only seconds after the fire begins and may even make the air flow change direction at the inlet; modelling this change of direction is quite a comprehensive task using one of the currently available modular simulation programs. The problem is solved in a crude way in the presented study, creating anew model each time the air flow rate crosses zero in any part of the system. This causes one simulation to become a series of simulations, each starting at the end state of the previous. The method can be used with any modular simulation program. This paper presents one of the scenarios from the fire simulations and shows the different problems that arise and how they are solved using NMF in combination with IDA and NEUTRAN.

1 The System Model

The platform shaft is a construction with a total height of more than 240 m; five separate ductwork systems represent the air supply and air extract to four separate air enclosures. The ventilation system is rather complex and quite a big model is necessary to forecast the changes in air flow rates and pressure levels when a fire develops in a specific location. To achieve this, a system model is built up from a library of single component models using a hierarchical strategy. Each of the ductwork systems are modelled and tested separately at normal operation (which is the initial condition of the fire simulations). In the next step, these "macro" components are connected to the air enclosures and fan systems to build the total model.

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1.1 General Description

The utility shaft is divided into four zones divided by gas tight decks (Figure 1). The four zones (air enclosures) are "Sump deck" (ENC1), "Crude pump deck" (ENC2), "Crude manifold deck" (ENC3), and "Maintenance deck" (ENC4). The zones ENC2 and ENC3 are classified as hazardous and are designed with a pressure 25 Pa lower than the pressure in the zones ENC1 and ENC4.

The access to the zones are via two parallel access shafts for normal access (Lifts) and for emergency access (Stairs). These are divided by an air lock between ENC1 and ENC2. The access shafts are used for ventilation as well, and are modelled as four rooms with negligible pressure resistance (UPPACC, UPPEMG, LOWACC and LOWEMG). They are pressurized at 87 Pa.

The air is supplied via three separate systems. Supply A (SAN) supports the non-hazardous zones ENC1 and ENC4. Supply B (SBN) supports the same zones via UPPACC, UPPEMG, LOWACC and LOWEMG. Supply C (SCH) supports the hazardous zones ENC2 and ENC3. The air is extracted via two separate systems. Extract A (EAN) takes the air from the non hazardous zones and extract B takes the air from the hazardous zones. Three fans provide the air flow. One fan (SU5) supports SCH. Another fan (SU6) supports SBN and SAN. A third fan, (EX5) supports EAN and EBH.

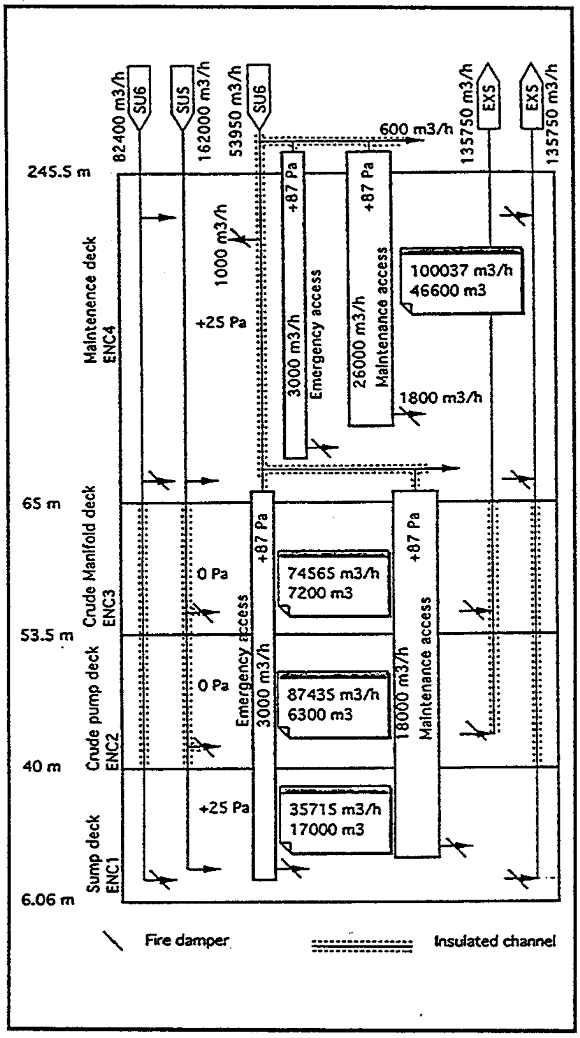

Figure 1.
Schematic Description of the Ventilation System

Key pressure levels and air flow rates at normal operation are indicated at Figure 1. Pressure levels inside the construction are relative to outside air at the same height at 21°C. This eliminates the influence on pressure from the elevation level at normal condition (all temperatures are assumed 21° C).

The design values are fetched from the background material of the construction which include detailed drawings and air flow calculations. Pressures and flow rates are taken from the drawings and the calculation listings. Equivalent flow coefficients for all pressure resistances in the IDA simulations are calculated by hand. An air duct is modelled as a general pressure resistance, and will usually include several bends and air dampers.

1.2 The Simulation Model

Because of the size of the problem, the system is divided into several sub-systems. Each sub-system is first separately run by IDA for steady state calculation, checking all air flow rates and pressures. After all sub-systems are checked for normal operation, the total system is connected. The five subsystems for the ventilation are shown in Figures 2 and 3. Each zone and fan system is also treated as a separate subsystem. The total system is shown in Figure 5.

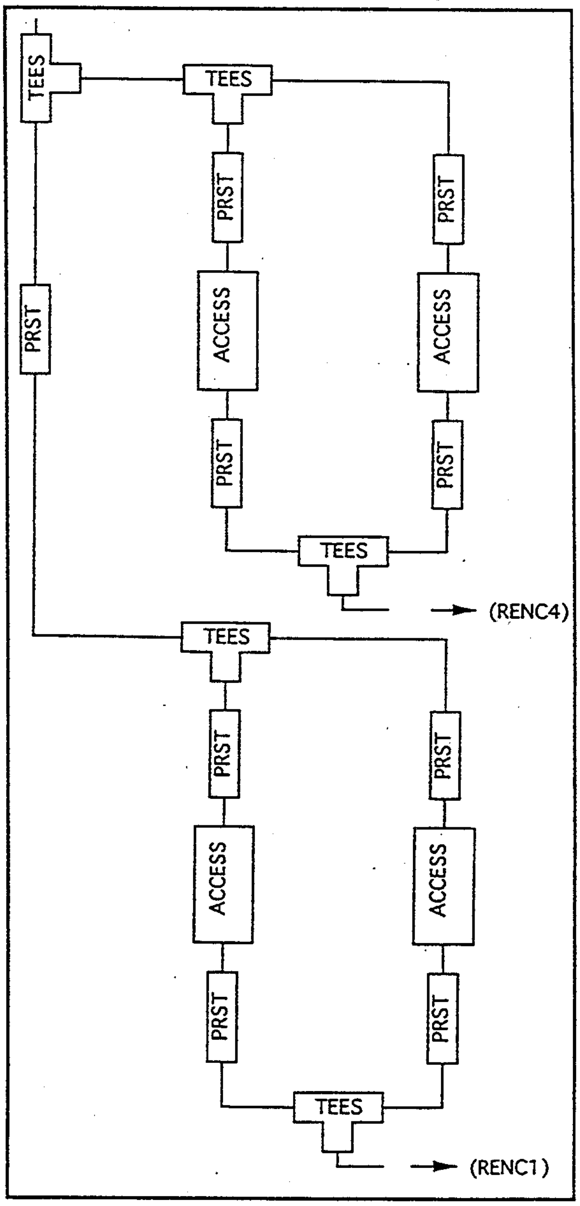

Figure 2.
Supply A, Non-Hazardous Ventilation System SAN

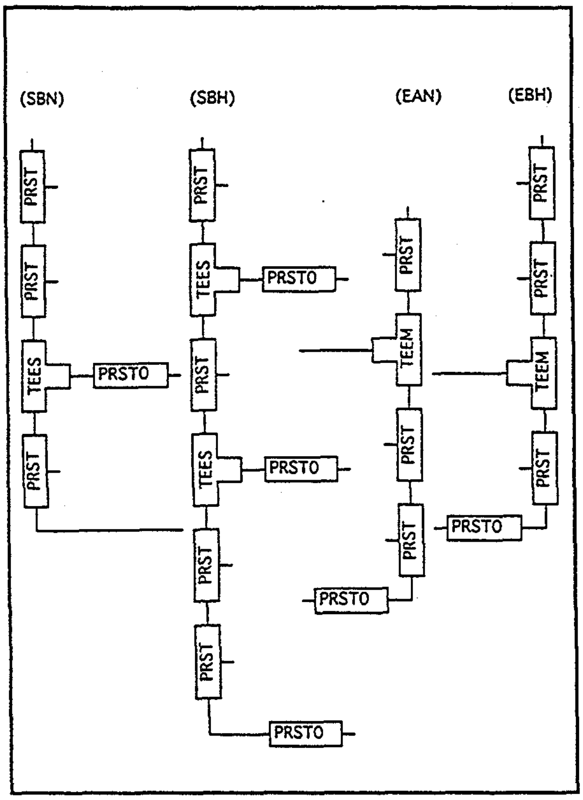

Figure 3.
Supply B and C (SBN and SCH) and Extract A and B (EAN and EBH)

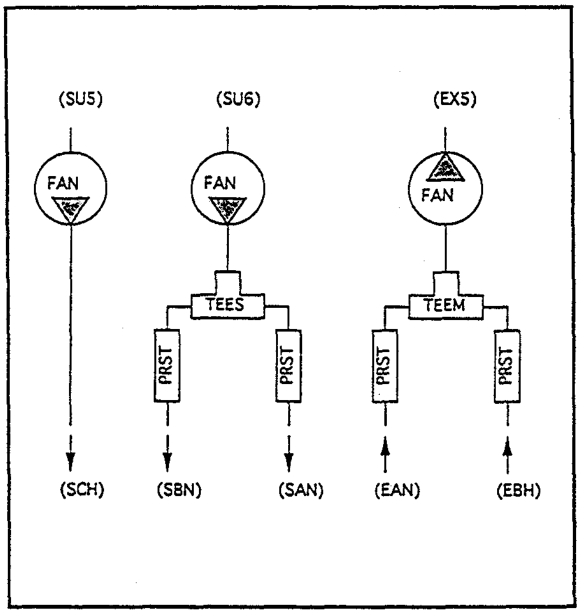

Figure 4.
The Fan System

1.3 Ventilation Channels and Stack Effects.

The ventilation channels are modelled as pressure resistances with the air volume flow as a square root function of the pressure difference, using a constant flow coefficient and treating the air as an ideal gas. The wall is modelled as a thermal node with a fixed film coefficient. The stack effects are calculated. Three different models are used in the simulations:

1. Ventilation channel with pressure resistance and stack effect (PRST)
2. Equal to the previous, but without pressure resistance (ACCESS).
3. Pure pressure resistance without stack effect. (PRSTO)

The NMF description of the first variant is presented in Figure 7, with global definitions in Figure 6.

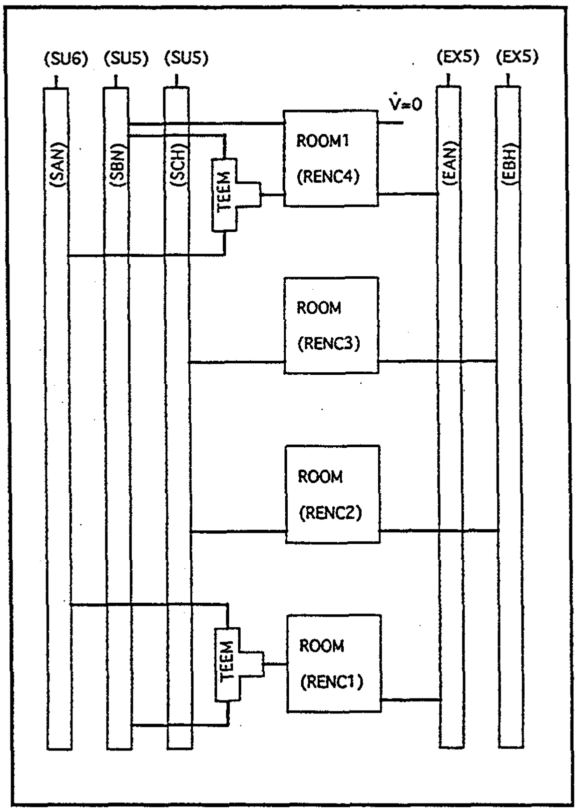

Figure 5.
The Total System

```
VARIABLE_TYPES
    Length       "m"          CROSS
    Area         "m2"         CROSS
    Volume       "m3"         CROSS
    Temp         "Deg-C"      CROSS
    Pressure     "Pa"         CROSS
    HeatFlux     "W"          THRU
    MassFlow     "kg/s"       THRU
    SpesVol      "m3/kg"      CROSS
    HeatCapA     "J/(m2 K)"   CROSS
    HeatResA     "(m2 K)/W"   CROSS

LINK_TYPES
    TQ       (Temp, HeatFlux)
    PMT      (Pressure, MassFlow, Temp)

CONSTANTS
   CP_AIR      1006.     "J/(kg K)"
   R_AIR       287.1     "J/(kg K)"
   KELV_ZERO   273.16    "Deg-C"
   P_ATM       101300.   "Pa"
```

Figure 6.
Global NMF Definitions

```
CONTINUOUS_MODEL Prst

ABSTRACT
"Pressure resistance with stack effect
 - Qadr. pressure resist. lin. around zero
 - Ideal gas law applied to air
 - Stack effect calculation
 - Wall with thermal mass
 - Thermal heat loss through wall
 - No thermal mass of air "

EQUATIONS
/* Local variable: Stack effect */
  DpStack := 9.81 * (Hi-Ho) / V;

/* Local variable: Tot pressure diff. */
  Dp := pi - po + DpStack;

/* Local variable: Heat from inside wall */
  Qwi := (a/rin)*(Tw-T);

/* Equation of state for ideal gas */
  ((pi+po)/2+P_ATM)*V = R_AIR*(T+KELV_ZERO);

/* Wall heat balance */
  a*cwall*Tw' = -Qwi + Qwo;

/* Room air heat balance */
  M*CP_AIR*(Ti-T) = -Qwi;

/* Volume flow versus pressure difference */
  M*V = IF dp>dplin then
          kv * SQRT(ABS(dp))
        ELSE_IF dp<-dplin then
          (-kv * SQRT(ABS(dp)))
        ELSE
          kvlin * dp
        END_IF;

/* External heat gain */
  Qwo = (a/rout)*(Ta-Tw);

LINKS
/* type     name        variables... */
   pmt      inlet       pi, POS_IN M, Ti;
   pmt      outlet      po, POS_OUT M, T;
   tq       wall_heat   ta, POS_IN Qwo;

VARIABLES
/* type     name    role [def [min max]] descr */
   SpesVol  V       LOC  1.2 "Spes. vol. of air"
   Pressure DpStack LOC  0   "Stack press. diff."
   Pressure Dp      LOC  0   "Press. diff."
   HeatFlux Qwi     LOC  0   "Inside wall heat"
   HeatFlux Qwo     OUT  0   "Outside wall heat"
   Pressure pi      IN   0   "Pressure at inlet"
   Pressure po      IN   0   "Pressure at outlet"
   Temp     T       OUT  21  "Bulk temperature"
   Temp     Ti      IN   21  "Inlet temperature"
   Temp     Ta      IN   21  "Amb. temperature"
   Temp     Tw      OUT  21  "Wall temperature"
   MassFlow M       OUT  0   "Massflow"

PARAMETERS
/* type      name  [def [min  max]] descr */
   generic   kv     1    "Flow coeff. [m3/s]"
   generic   kvlin  1    "Lin. flow coeff. [m3/s]"
   Area      a      1    "Wall surface area"
   HeatResA  rin    1    "Internal heat resist."
   HeatResA  rout   1    "External heat resist."
   Length    hi     0    "Inlet height"
   Length    ho     0    "Outlet height"
   HeatCapA  cwall 1000  "Thermal wall mass"
   Pressure  dplin  1    "Limit when linear"

PARAMETER_PROCESSING
  kvlin := kv/sqrt(dplin);

END_MODEL
```

Figure 7.
NMF Description of the Ventilation Channel with Stack Effect.

1.4 The Fire-Room Model

The room air is modelled as simply as possible. Since we intend to study the qualitative effects from the fire, our system is a study of the effects on the total ventilation system, assuming a constant heat load from the fire. The following is assumed:

- One single zone with fully mixed air.
- Fires modelled as a pure heat load with a given value.
- No modelling of the combustion processes.
- The air is treated as an ideal gas using properties of pure air.
- Neglecting kinetic energy.

The walls are assumed to keep a uniform temperature, using a constant heat transfer coefficient and a fixed fraction of radiative heat from the fire. NMF description of the fire room is shown in Figure 8.

```
CONTINUOUS_MODEL Room

ABSTRACT
  "A room with thermal air mass. Air expansion.
   One inlet and one outlet"

EQUATIONS

/* Equation of state for ideal gas */
   (P+P_ATM)*V  = R_AIR*(T+KELV_ZERO);

/* Mass conservation */
   MflIn + MflOut = -Vair*V'/(V*V);

/* Energy conservation */
   Q =   Vair/V*(CP_AIR-R_AIR)*T'
       - Vair*V'/(V*V)*(CP_AIR-R_AIR)*T
       - MflIn*CP_AIR*TIn
       - MflOut*CP_AIR*T;

LINKS

/*    type  name     variables... */
      PMT   Inlet     P, POS_IN MflIn, TIn;
      PMT   Outlet    P, POS_IN MflOut, T;

VARIABLES

/* type       name   role [def [min  max]]  descr*/

  MassFlow  MflOut  OUT  1          "Outlet massfl."
  MassFlow  MflIn   IN   1          "Inlet massfl."
  Temp      T       OUT  21         "zone temp."
  Temp      TIn     IN   22         "Inlet air temp."
  pressure  P       IN   0          "Pressure"
  HeatFlux  Q       IN   20000      "Heat load"
  spesvol   V       OUT  0.83086    "Spes. vol. of air"
  Volume    Vair    PAR  1000       "Enclosure vol."

END_MODEL
```

Figure 8.
NMF Description of the Fire-room.

The tall room, ENC1, is a variant of the room model named ROOM1, which has air inlet and outlet at two levels and stack effect calculation.

2. System Definition Using NEUTRAN

The "Links" concept of NMF has two major advantages. The bundling of several variables into one link, describing a physical connection between the model and its environment, makes the number of connections the user must interfere with smaller. The second concept is related to the flow variables, which are preceded by one of the keywords POS_IN or POS_OUT for definition of the flow direction where the variable is handled as positive. Using the information that is provided by NMF, it is possible to automatically create a connection between all variable pairs with the correct sign change. If two flow variables from two models are connected, then the sign of one of the variables has to be changed if both variables are defined as either POS_IN or POS_OUT. In IDA, this sign change is part of the input data. With other programs, it might be necessary to introduce an extra component to do the sign change.

NEUTRAN has the ability to read a simple problem specification file with the connections at the NMF link level and automatically create an IDA input file. Because the IDA input file requires the connections variable by variable, the translator has proved to be extremely useful. The variable names are encapsulated inside the links together with the sign convention. Sign errors in the connections are totally eliminated at the system level, a kind of error that may be very difficult to discover.

Imagine one room, ENC1, and one pressure resistance, PRST1, connected to the air outlet of the room. The connection line in the system definition file would be:

ENC1.Outlet = PRST1.Inlet

NEUTRAN translates this into three variable level connections for the IDA input file (note the minus sign in the second connection):

ENC1.P = PRST1.Pi
ENC1.MflOut = -PRST1.M
ENC1.T = PRST1.Ti

3. The Simulations

Several simulations are carried out. The present case is a fire at the sump deck (ENC1). The fire is caused by a smaller oil leakage, making a pool of 4 m^2 at the floor. If the oil is light, density=740 kg/m^3, and the heating value is 42000 kJ/kg, then this will generate a heat flow rate as a function of time, that under specific conditions (Drysdale 1985) is calculated to have a maximum of 7200 kW. In the calculations, this power is assumed constant until limitations in the oxygen concentration eventually occur.

The fire dampers in the previous construction are located at all air inlets and outlets, and are designed to close at 70°C. The simulation presented here shows cases with fire dampers at the air inlet only.

During the first 18 seconds, the inlet air flow turns in one of the air inlets of room ENC1, causing the air to flow the opposite way into SBN. After that point, an error in input data has unfortunately been introduced, causing the fire heat to have increased influence. This error, and not the fact that the air flow resistance is actually higher when air flow turns, causes most of the discontinuity in the first derivative of the pressure and mass flow in Figure 9. At the moment when this air flow turns, the temperature is 26°C, a too-small increase to give significant increase in resistance, which theoretically introduces the same kind of discontinuity because of the static model of the ventilation system. After 43 seconds, the air is blowing heat back through both air inlets, as seen in Figure 9. After 133 seconds, the air temperature has reached 70°C, and the inlet air dampers close. This causes the pressure and outlet air flow rate to increase.

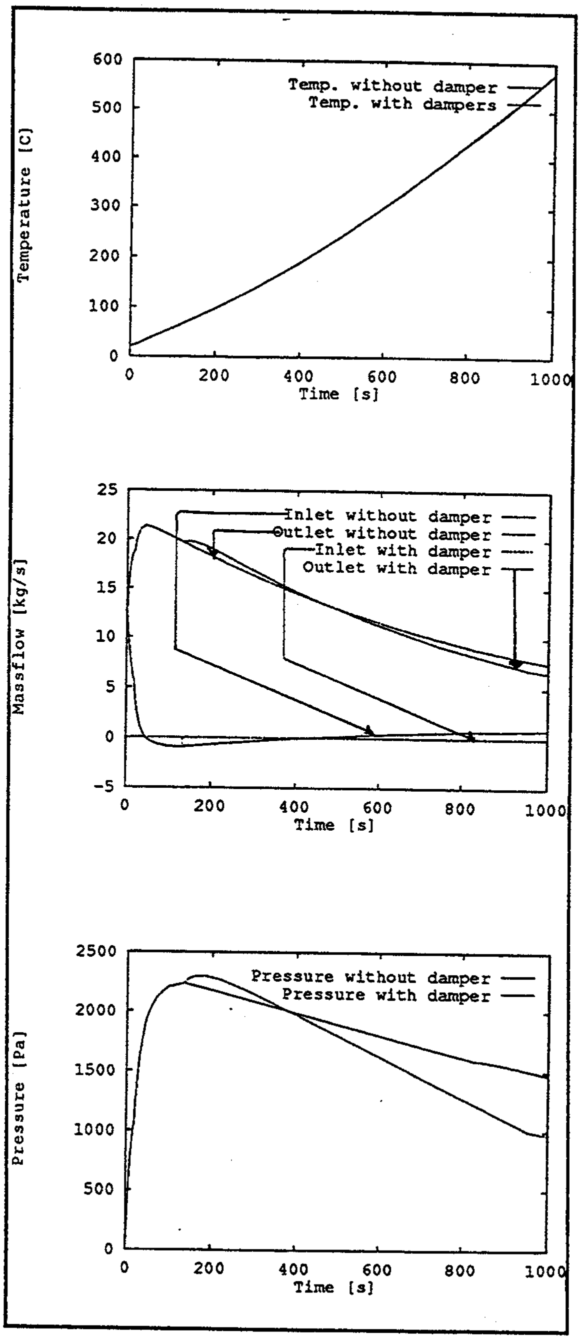

Figure 9.
Simulation Results

Assuming constant heat after this time is only of theoretical interest. However, the simulations show that the air flow at one of the air inlets turns the other way again if the dampers are open. We also see that the pressure rises when the dampers close, but falls quicker to a level, even below the level where the dampers are open. This is because of the same effect. All results after the temperature has reached 50-100°C must be evaluated carefully because many effects are not modelled properly for that study. The model is only valid in a small range around the operating condition, and the simulations must be accompanied by experiments.

As we have seen, air flow rate turns the opposite way several times. Each time the air flow rate changes, the model is no longer valid, even if the simulation still runs. The problem is avoided by redesigning the system each time air flow rate crosses zero any place in the system. The event handling mechanism of IDA is used to detect the situations when air flow rates reach zero and stop the simulations. The work is then to substitute the link "INPUT" with the link "OUTPUT" for air channel models and replace the tee-pieces for mixing with tee-pieces for splitting. Using NEUTRAN, this is not too complicated.

The biggest problem is to achieve the correct starting values. At the point when the IDA simulation stops, the values of all variables are written to a file with the same format as the intial value file read by IDA at the start of the simulation. When turning a model the opposite way, some initial values must also be moved. This is especially true for the tee-pieces. Therefore, some manual work is necessary before starting one simulation from the end of the previous.

The work could be done easier by designing several versions of each component in the NMF and allowing the names of the variables and links to be the same. Only the component names have to be changed. The same variable will always keep the same value in the global system. The drawback is that you need one different NMF description for each configuration of air flow directions. For ventilation channels, you need two versions, and for tee-pieces you need six versions of each model. The method is not suitable for models with varying numbers of interfaces.

Since that approach violates the simplicity behind the NMF, which is one of its most important ideas, it is not attractive as a general approach. There is obviously a need for a better way of solving bi-directional flow problems using NMF. A more elegant method is proposed by Per Sahlin (Bring and Sahlin 1993) and utilizes extra variables at the model interfaces. The author has recently applied it to a simple fire simulation problem, which runs under IDA.

4. Conclusions

The use of IDA, together with NEUTRAN, has proved to be an efficient tool for building complicated system models. Especially, the use of NMF and its Link concept has proved to reduce model building effort significantly.

For fire simulations, the modelling of bi-directional flow between components is of great importance. Restarting the simulation when the air flow rate crosses zero is a straight forward but time-consuming way of working.

To go further, the concept of writing bi-directional components in NMF using links with an additional variable seems to be the most interesting concept (Bring and Sahlin 1993). A few bi-directional components have already been tried with good results using IDA. Further work needs to be done to create complete model libraries with bi-directional flow and test them using different simulation environments.

References

Bring and Sahlin 1993

Axel Bring and Per Sahlin. "Modelling Air Flows and Buildings with NMF and IDA", Dept. of Building Services Engineering, Royal Institute of Technology, S-100 44 Stockholm, Sweden. Proceedings, IBPSA '93, Adelaide, Australia, August 1993.

Bring, Sahlin and Sowell 1992

Axel Bring, Per Sahlin and Edward Sowell. "The Neutral Model Format for Building Simulation", Dept. of Building Services Engineering, Royal Institute of Technology, S-100 44 Stockholm, Sweden. [Bulletin No.24, ISSN0284-141X,

ISRN KTH/IT/M--24--SE]

Bring 1990

Axel Bring, "IDA SOLVER, A Users Guide", Department of Building Services Engineering, Royal Institute of Technology, Stockholm, Sweden

Drysdale 1985

Dougal Drysdale, **An Introduction to Fire Dynamics**, John Wiley and Sons Ltd. 1985

IDA 1991

Axel Bring and Per Sahlin, "IDA SOLVER, A TOOL FOR BUILDING AND ENERGY SYSTEMS SIMULATION", Proceedings of Building Simulation '91 conference, France.

Kolsaker 1990

Kjell Kolsaker, "DYMAMISK SIMULERING MED IDA. Et praktisk verktoy for bygningssimulering med modellbibliotek for fjernvarmeinstallasjoner". Technical report ISBN 82-595-6091-7,

SINTEF, Trondheim, Norway

Sahlin and Sowell 1989

Per Sahlin and Edward Sowell, "A Neutral Format for Building Simulation Models", Proceedings of the Building Simulation Conference, Vancouver, Canada, June 1989.