Thermal Flow Sensor Modeling Using Electronic Circuit Simulator

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1. Introduction.

Computational fluid dynamics (CFD) modeling becomes more and more popular in Mass Flow Controller (MFC) design [1]. Preliminary modeling helps understand MFC functioning, envision potential problems, and thus reduce hardware development time. However, using CFD software is quite a challenging task. It requires accurate and detailed description of gas properties and MFC geometry, powerful computational resources, and certain skills to operate the software. Modeling process itself is very time consuming, and any iteration of design may require significant amount of time.

A different approach requires much less time and efforts for modeling and iterations, still providing reliable results. The idea is to simplify the model as much as possible by identifying key factors affecting system performance, and removing all other factors from consideration. To some extent, this approach can be characterized as *qualitative* modeling, since it is not intended to give true numerical results. A typical question simplified modeling can answer the best is: if some parameter changes, what *direction* the system response would be.

A simplified modeling can be easily performed by electronic circuit simulation software [2]. Electronic circuit simulators are often used for modeling processes in different engineering and physical disciplines other than electronics for several reasons. First, electrical analogies for disciplines such as thermodynamics, mechanics, fluid dynamics, to name a few, have been developed over time. A simplified electrical model of physical process usually gives reasonably accurate qualitative solution, yet providing very fast simulation. Second, when the complex process consists of parts from different disciplines, transferring everything to one (electrical) domain is beneficial, since the whole process can be simulated in one simulation environment. And last but not least, circuit simulators are cheap, user-friendly and easy to learn to use, due to high demand and popularity among engineers and students.

Apparently, creating an adequate electrical model of the process is essential for obtaining solid and trusted results. To do that, a designer must have at least basic knowledge of electricity and understanding of simulated physical process. However, such an understanding is obviously required from anyone performing CFD modeling, as well as any other modeling methods.

2. Model.

As an example, modeling of thermal mass flow sensor is presented. Thermal sensors are typically used in high accuracy mass flow meters and controllers. With minor variations, sensor design has been pretty much standard for many years [3]. The sensor consists of capillary tube and two coils (**Fig.1**). Each coil serves as a heater and a temperature sensor at the same time. Coils temperature is balanced at no flow condition; at flow temperature difference between coils is proportional to mass flow.

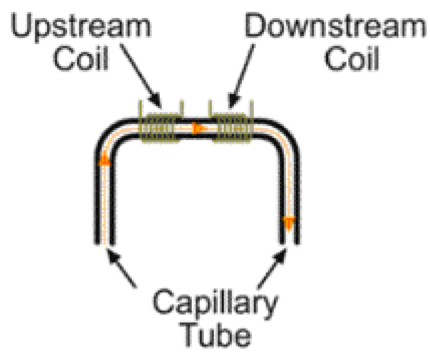

Fig.1

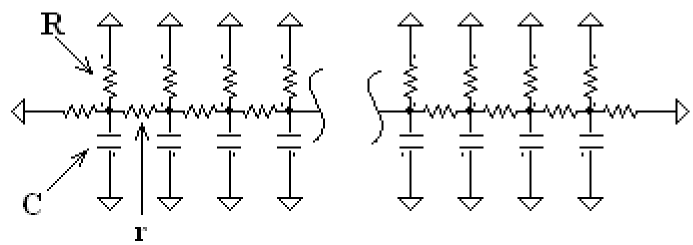

Fig.2

The **NL5 Circuit Simulator** has been used to model thermal sensor in electrical domain [4]. The simulation method used by NL5 is different from popular Spice-based simulators, and provides very fast and robust simulation.

The first step is capillary tube model. According to heat-electricity analogy, resistors represent thermal resistance (reciprocal of thermal conductance) of the media, capacitors - heat capacity of the media, voltage and current correspond to temperature and heat flow, respectively. A simple one-dimensional model consists of resistors, representing thermal resistance of insulator (**R**) and combined thermal resistance of tube and gas (**r**), and capacitors (**C**), representing combined heat capacity of tube and gas. Insulator resistors, as well as both ends of the tube, are connected to the ground, which represents ambient temperature (**Fig.2**).

A simple model of the coil consists of current source, representing a heater, and a voltmeter, measuring temperature (**Fig.3**). More "realistic" model has a number of current sources, providing distributed heating along the coil, and number of summing operational amplifiers measuring averaged coil temperature. After adding a second coil and subtracting coils temperatures by differential amplifier, the model is complete and ready for simulation (**Fig.4**). Voltages ***V1*** and ***V2*** represent coil signals, and the difference ***Vs*** is a resulting sensor signal.

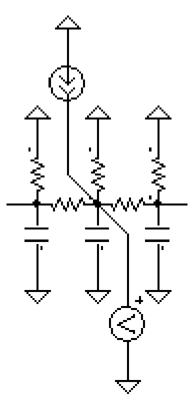

Fig.3

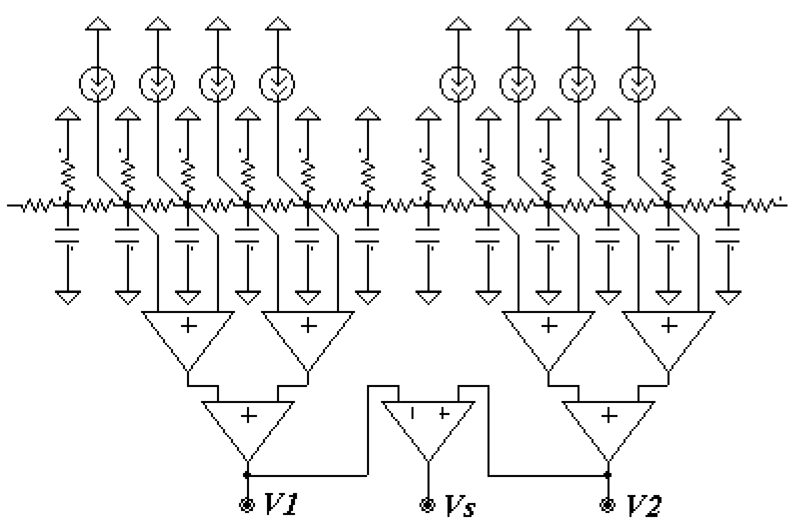

Fig.4

This model represents only heat transfer due to conduction. It can be used to calculate, for instance, temperature distribution along the tube, but only at no flow condition. Gas flow introduces so called "forced heat convection" mechanism, where heat is transferred by the movement of the gas media. In electrical model, a heat stored in the gas is represented by an electrical charge stored in capacitors, so that capacitors are electrical equivalents of gas substance. Gas flow inside the capillary tube is literally equivalent to "physical" movement of capacitors along the circuit. To perform exact simulation of this process, capacitors should be periodically disconnected from one schematic point and then connected to another point, thus imitating gas flow. Such a reconnection should occur with the rate proportional to gas velocity.

Simulating such "jumping capacitors" is obviously not a good idea, since it significantly complicates schematic. A possible modification of the method transfers charge from one capacitor to another with the rate proportional to gas velocity, using controlled switches. Still, any kind of switching requires a lot of computation, which affects simulation speed. Since the intention of electrical simulation is ability to modify the model and obtain results very fast, a different approach is suggested.

Instead of transferring the charge from capacitor to capacitor, gas flow is simulated by continuous current (heat flow), which transfers charge (heat) exactly as gas flow does. The heat flow should be proportional to gas heat capacity, gas velocity, and local temperature. This can be done by voltage controlled current source **G** with the gain equal to product of capacitance **C** and gas velocity ***v***, and controlled by the local voltage (temperature) (**Fig.5**). Thus, setting current source gain **G** = **C******v*** models both gas heat capacity and gas flow effects.

For steady state condition, when temperature distribution is not changing with time, all capacitors can be removed from the circuit. Gas heat capacity will still affect temperature profile, since it is included into current source gain. Final, and the simplest, model of capillary tube with gas flow consists of only restive network and controlled current sources (**Fig.6**), and can be simulated with fastest speed possible.

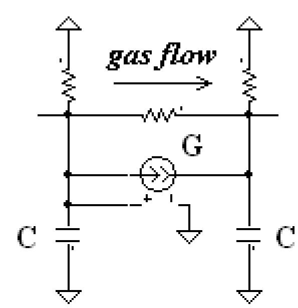

Fig.5

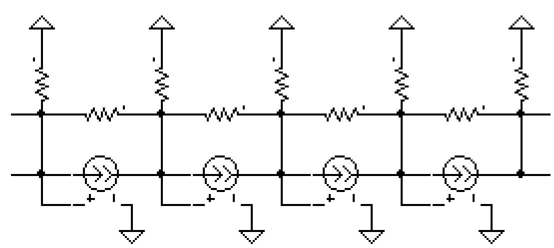

Fig.6

3. Results.

Temperature distribution along the capillary tube simulated at different flow rates is shown on the **Fig.7**. Averaged temperature of the first (upstream) coil and the second (downstream) coil is decreasing with flow, while the temperature difference is increasing, thus providing a signal proportional to the flow. Averaged coils temperature and sensor signal are shown on **Fig.8**. As flow increasing, the sensor signal reaches the maximum, and then starts

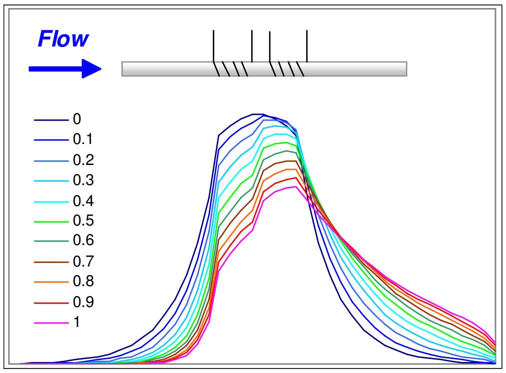

Fig.7

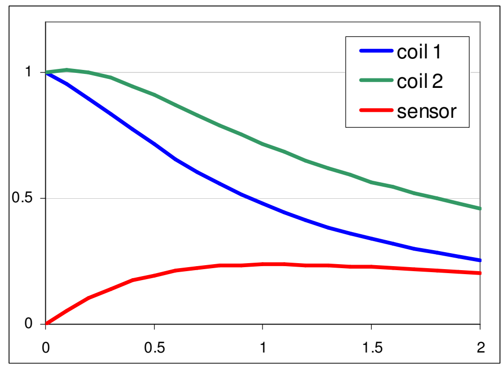

Fig.8

decreasing. This **non-linearity** effect is typical for "constant current" method of thermal flow sensor operation. The non-linearity is observed on real sensor data; it can also be easily obtained analytically. **Fig.9** shows excellent correlation between simulation data, analytical solution, and measured response of the real sensor.

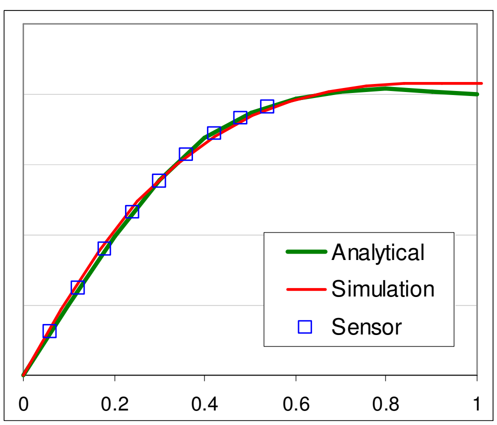

Fig.9

Electrical model also makes it possible to simulate sensor performance for **different gases**. Gas properties mostly effecting sensor behavior are heat capacity and thermal conductivity of a gas. Another important contributor to sensor behavior is heat transfer between a gas and a capillary tube wall – heat transfer coefficient is different for different gases. Simulation has been performed for 4 popular in semiconductor industry gases (N_2, SF_6, Ar, He), and compared with real sensor data. Taking heat capacity into account is the easiest part, since heat capacity of these gases is well known, and heat capacity of the tube and insulator does not affect sensor readings. Modeling effect of thermal conductivity and heat transfer, however, is problematic for many reasons, and requires slight modification of the schematic.

As a first step, modeling of four gases flow has been performed with the same value of thermal conductivity and heat transfer coefficient (**Fig.10**). The results show good correlation with real sensor data at low flow, however at high flow the difference is significant. Using different, empirically found heat transfer coefficients for different gases, makes the perfect match of the data in wide flow range (**Fig.11**).

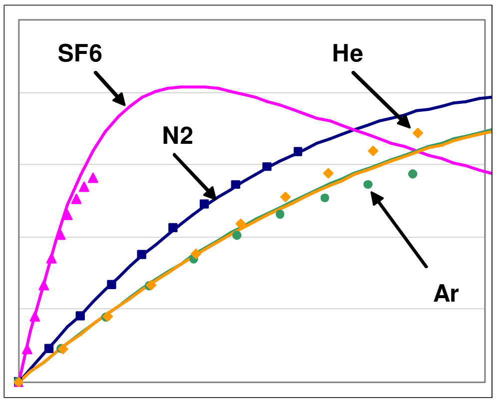

Fig.10

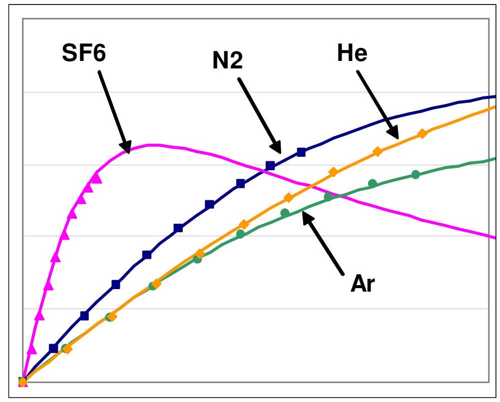

Fig.11

Electrical modeling capability is not limited by examples presented. Different **geometry** of the sensor, such as coil width and distance between coils, can be modeled by connecting heater current sources and sensing summing amplifiers to different points of capillary tube. Another popular method of flow sensor operation – **constant temperature**, can be modeled by adding control electronics, maintaining coils voltage (temperature) at specified level. Most challenging **flow transient** simulation requires returning capacitors back to the circuit, which increases simulation time a little bit, but still provides reliable results.

4. References.

1. MFC design for semiconductor processing using computational fluid dynamics. R.Mike McDonald. *Solid State Technology*, November 2007, pp 32-37.

2. Modeling micropumps with electrical equivalent networks. Tarik Bourouina *et al* 1996 *J. Micromech. Microeng.* **6** 398-404

3. US Patent 4,517,838. Wachi et al. Thermal Mass Flow Meter. 1985.

4. NL5 Circuit Simulator. http://nl5.sideliensoft.com