SigmaPipe 3D Pipe Flow and Heat Transfer

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Abstract

Plant engineers are trained to solve problems involving pipe flow and heat transfer, but in practice they often do not have time to perform such calculations in detail. Although many software packages are available, most require (i) licence fees and (ii) significant time investments to learn how to use them. As a result, these packages tend to be used more in dedicated design situations and are not applied “casually” on the plant.

SigmaPipe is a 3D pipe flow and heat transfer package which has recently been developed (locally, in Perth) to provide engineers with a free, easy-to-use tool for such situations. It combines standard plug-flow engineering calculations (for heat transfer and pressure drop) with 3D object programming. The result is a pipe flow “video game” where the user can nominate the type of fluid (from a database) and set up a pipe flow path. After solving, the user can then visualise pressure drop, fluid temperature, Mach number, heat flux etc as a colour gradation along the pipe wall.

The vision for SigmaPipe is that it will become a standard tool for graduate engineers. Projects for evaluating it are under way at Curtin and Monash Universities in 2014. At present, SigmaPipe is limited to single-line systems (one fluid source and one fluid sink, with multiple such lines allowed). In terms of further development, “the sky’s the limit”. Depending on user feedback, future versions will most likely involve multi-line splitting and mixing, multi-phase flash separators and (possibly) pneumatic solids conveying.

Introduction

In the area of pipe flow and heat transfer there are many available simulation packages (current examples include AFT Fathom (1), Pipe Flow Expert (2) and Fluidflow3 (3)). For a new one such as SigmaPipe to establish itself and find a niche, what are the requirements and how does it differentiate itself? To answer this, it is perhaps necessary to first consider how the concept arose.

In the engineering support section of an operating plant (HIsmel Kwinana 2003-2008) there were several young engineers who, from time to time, needed calculations related to orifice sizing and/or pressure drop. An overriding consideration was always time – they needed reliable results fast. There was no question of them buying a commercial package and learning how to use it, since this was regarded as something for specialist design engineers within stand-alone engineering companies. In any case, the engineer in question might not need such a calculation again for six months or more. If they had bought a commercial package and learned to use it, they would (six months later) most likely have forgotten how to use it. If such a (commercial) tool is not used constantly, the cost is usually not justified...

How, then, could these engineers get the job done? In this particular case word spread that one individual (Rod Dry) had some (not particularly user-friendly) Excel software that could perform such calculations. It became easier to ask this person to do the calculations, and this became the default option. Of course, all is well if such a person is available and is happy to help when needed. However, this is not always the case. The thought-process this triggered was as follows:
1. The problem is truly universal for time-poor engineers in operating plants.
2. There is currently no (free, easy-to-use) piece of software for this.
3. Such a tool needs to be introduced at undergraduate level as a learning aid.

Apart from the need for zero cost and a high level of user-friendliness, the greatest requirement is for sufficient "residual familiarity". The engineer needs to have sufficient memory of using it (e.g. from undergraduate days) such that using it again (after a certain period) is not perceived as a daunting task.

SigmaPipe is a response to this perceived need. Key “design” elements are:

- It is essentially a community service project (the engineering community in this case).
- It is designed as a standard Windows application in terms of menus, editing etc.
- The user must be able to create and manipulate pipe-related objects in 3D space.
- Flow solutions are essentially “plug flow” in nature – this is not a CFD package.
- As far as possible, physical reality must be reflected (e.g. if pipes heat up, they grow).
- The system must deal (seamlessly) with sonic limitations (e.g. choked flow orifices).
- Common elements (e.g. valves, pumps and heat exchangers) must be included.
- It needs to be introduced to users as a teaching aid at undergraduate level.

With these guiding principles, coding started in early 2009. The first major release version (as a free download from www.sigmapipe.com) went on-line in January 2013 and the second (SigmaPipe 2.0) in January 2014.

**SigmaPipe Features: Setting Up a Pipeline**

At its most basic level SigmaPipe uses a fluid source, a collection of pipe sections and a fluid sink. Figure 1 shows a very simple system involving two pipe sections, one in carbon steel and the other in copper.

Pipe sections may be constructed from any of 21 standard “on-board” materials (carbon steel, 316 stainless, copper, cement, PVC plastic, etc). User-defined materials of construction can also be used. For example, if a user would like to specify carbon steel with a given wall roughness ratio, then a new material (based on the existing carbon steel) can be defined and wall roughness can be set to the desired value.
Pipe diameters (ID and OD) can be defined (i) in terms of standard sizes (e.g., DN200 Sch 40) or (ii) as user-defined ID and wall thickness. Internal lining and external cladding options are shown in Figure 2—the user can define a single external cladding layer or a single/double internal lining layer.

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**Figure 2**  
Lining and Cladding Examples

Conditions outside the pipe (ambient air) can be defined in the usual way (temperature, pressure, humidity, wind speed) and the pipe will interact with this (global) ambient set of conditions in terms of heat transfer. Wall temperature gradient and wall heat flux will be monitored and reported, together with wall stress generated as a result of wall heat flux. This will lead, in general, to the pipe wall temperature being different to ambient temperature. As a result, the size of the pipe (length in particular) could change. This geometry change is monitored and shown in 3D in the result set.

At times, parts of the external pipe could be exposed to something other than global ambient conditions. As shown in Figure 3, SigmaPipe allows for three different types of external “process container” that give rise to different external wall heat transfer conditions:

(i) Gas furnace box (typically hot flue gas at a given temperature and gas velocity)
(ii) Saturated steam box (saturated steam at a given pressure)
(iii) Cooling water box (at given temperature and average water velocity).

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**Figure 3**  
External Process Containers
The pipe section inside each box will experience “local ambient” conditions as defined by the box object, not by the global ambient settings. Of course, any pipe section that is outside a process box will experience normal (global) ambient conditions.

These, then, are the basics of how SigmaPipe deals with pipe sections. Of course, plain straight-pipe objects are not enough – some of the other standard object types are shown in Figure 4.

The user can assemble these pipe element types in any desired combination. After assembly it is also possible to edit individual elements and, if necessary, to resize the whole line.

The next issue is selection of a fluid type. Currently available fluid types are:

- Argon Gas (Ar)
- Oxygen (O₂)
- Nitrogen (N₂)
- Water/Steam (H₂O)
- Carbon Dioxide (CO₂)
- Carbon Monoxide (CO)
- Methane (CH₄)
- Ethane (C₂H₆)
- Ethylene (C₂H₄)
- Propane (C₃H₈)
- n-Butane (n-C₄H₁₀)
- Ammonia (NH₃)
- Hydrogen Sulphide (H₂S)
- Sulphur Dioxide (SO₂)

The user may nominate any mixture of these types (at user-defined supply temperature and pressure). At this point only Raoult’s law interaction between components is assumed – this is an area for further development. For each fluid type a wide range of thermodynamic and transport properties are stored in a database, including thermal conductivity, speed of sound etc. For water/steam the full range of ASME97 steam table equations (4) is used, and for the others NIST data
(5) are generally used. Where necessary, extrapolation is used to allow simulation over the temperature range 100-3000 K (-173 to 2727°C) and pressure range $10^{12}$ to 500 bar absolute.

It should be noted that adding a user-defined fluid is not a simple matter. Data consistency and range are major issues and significant testing is needed to ensure data integrity. For now it must be accepted that adding further fluid types is a development item. The current fluid database is aimed at typical plant systems involving utilities, combustion/gasification, steam cycles and natural gas processing. It is expected that these will adequately cover a large proportion of situations encountered by plant process engineers.

The final selection item for the user is defining a fluid sink. In SigmaPipe a fluid sink object may be regarded as a constant-pressure “black hole” into which fluid disappears. Pressure in the sink is the only item the user needs to define.

**SigmaPipe Features: Solving and Viewing Results**

Once a fluid source, a pipeline (combination of pipe elements) and a fluid sink are in place, the user can solve the model. A description of the underlying models used for pressure drop and heat transfer is given in the Appendix. The user can then examine the results (i) as a colour gradation along the pipe wall as illustrated in Figure 5, or (ii) as a result graph as shown in Figure 6.

![Figure 5](Image)

**Figure 5**  Colour Gradation Example (Showing Fluid Pressure)

![Figure 6](Image)

**Figure 6**  Result Graph (Showing Pressure, Temperature & Mach Number)
Other output features include an ability to toggle the pipeline between ambient and process temperatures in order to “see” the degree of thermal expansion. Fixed points and linear thermal expansion compensators can be defined to assess movement allowances and mechanical integrity strategies.

Each material of construction has a stress vs temperature curve which defines the yield point. When a fluid flow solution is calculated, SigmaPipe also computes wall stress as a percentage of yield stress at the prevailing process condition. If yield stress (or, more precisely, yield stress divided by a user-defined safety factor) is breached, SigmaPipe reports this as a pipe wall integrity failure. Pipe wall integrity is included as a “standard” output result the may be viewed in the same way as any other output variable.

SigmaPipe Feature: Multiple Lines

SigmaPipe currently allows only simple lines (one fluid source, a pipeline of some description and one fluid sink). It does, however, allow the use of multiple such lines. Figure 7 shows a hot offgas duct formed from 90 separate cooling water lines. Individual lines may, of course, be modified to install local bends in order to create instrument openings etc.

SigmaPipe Limitations and Development Options

Primary technical limitations relating to the current version (SigmaPipe 2.0) are as follows:

1. User-defined fluids are not permitted.
2. Only single-line pipe systems are allowed, with no line splitting or mixing.
In general, the issue with “casual” user-defined fluid types is that they could give strange results due to the uncontrolled nature of the fluid type data. New fluid types can certainly be added in future but, as described earlier, this needs to be done formally at source-code level due to the requirements for data consistency and integrity.

The next version of SigmaPipe is likely to include line splitting and mixing. Stream splitting naturally calls for component, phase and flash separators. Feedback from current users will most likely determine how and when this is implemented. Introduction of splitting and mixing is a big step, because it will extend the capability of SigmaPipe into the area of formal plant design. It is also a serious code development task and some form of collaboration may be needed to achieve it.

In principle, it is also possible to develop solids handling capability in SigmaPipe. Collaboration with at least one bulk materials handling equipment supplier may be considered a prerequisite for this.

Ultimately there is no reason why chemical reactions cannot be included. The result, in this case, will be a flowsheet development tool with full 3D capability. This option is currently considered to be further in the future (compared to the other options outlined above). The reason is that all the preceding features will be needed (anyway) in the chemical reaction version.

A parallel development option relates to language translation. Although SigmaPipe is currently available (only) in English, internal code structure envisages the use of other languages (eg Chinese, French or Spanish). The action required to activate another language is quite simple – what is needed is translation of a (fairly long) list of English-language text strings into the language in question. Of course, this translation service (plus iterations to “get it right”) needs to be provided on the same type of “community service” basis that underpins the rest of SigmaPipe. In other words, a degree of “user-pull” is needed to make this happen.

**Biography**

Dr Rodney James Dry (FTSE) is currently Manager, Development at Hlsmelt Corporation (owned by Rio Tinto) in Perth. He has been in this role since 1995 and is deeply involved in the development of Hlsmelt and Hlsarna direct ironmaking processes.

Before joining Hlsmelt Rod was a Research Manager at the CSIRO Division of Minerals in Melbourne (1984-1987) where he undertook development of fluidized bed technology applications for the minerals industry. From 1984 to 1987 he lectured in Chemical Engineering at Monash University in Melbourne, and prior to this (1980-1984) he was a process engineer with Sasol (synthetic fuels production from coal) in South Africa.

**References**


4. ASME Steam Tables for Industrial Use: [https://www.asme.org/products/books/asme-international-steam-tables-for-industrial-use](https://www.asme.org/products/books/asme-international-steam-tables-for-industrial-use)

Appendix: Sub-Models Used for Pressure Drop and Heat Transfer

Pressure Drop

The methods used are those found in in Chemical Engineering Volume 1 (3rd Ed) by J M Coulson and J F Richardson (Pergamon Press, 1977). Single-phase pressure drop is evaluated via standard friction-factor expressions plus static head and standard velocity head pressure loss factors for bends, orifices etc. Two-phase pressure drop is determined via Lockhart-Martinelli expressions as presented in Chemical Engineering Volume 1 (Coulson and Richardson).

For critical flow situations sonic velocity (at prevailing conditions) is monitored for each fluid type. This is considered part of the data-base on each chemical species (along with enthalpy, entropy, viscosity, thermal conductivity etc) as a function of temperature and pressure. For mixtures of chemical species a molar average sonic velocity is used. The solver (in variable flow mode) then monitors for actual velocities in excess of sonic velocity and limits flows to a maximum of Mach 1.

Heat Transfer

For single-phase flow, laminar heat transfer coefficients are evaluated using the Hausen correlation and for turbulent flow the Sieder-Tate equation is used. Both are taken from Perry's Chemical Engineer’s Handbook by R H Perry and D Green, McGraw-Hill, 6th Ed (equations 10-49 and 10-50 respectively). For transitional flow (between laminar and turbulent) the expression from Chemical Engineering Volume 1 (Coulson and Richardson) given by equation 7.60 is used.

For boiling heat transfer the Shah correlation as presented in ASHRAE Trans Vol 82, No 2, pp 66-86 is used. For condensing heat transfer the methods outlined in Section 2.6 of HEDH Rev 1996 (Begell House) are applied.

Sub-Model Verification

Internal verification of these sub-models has been performed as part of the development process. This includes checks against data from sources such as Perry 6th Ed and “Flow of Fluids through Valves, Pipes and Fittings” by Crane Australia, St Marys, NSW.

There is no claim that SigmaPipe is error-free in this regard. The developer can only go so far, then user feedback becomes the primary vehicle for identifying issues. External verification and/or error identification (by users) is actively sought and is most welcome. Sub-model corrections and/or improvements will be implemented routinely with each new version of SigmaPipe.

Pilot projects involving the use of SigmaPipe are currently under way at two Australian Universities in 2014. Feedback from these projects will (most likely) have some bearing on this.