Modeling/simulation of battery safety applied to aeronautics

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Abstract

The need for Li-ion batteries is essential both for the more electric aircraft and for all new forms of all-electric or hybrid-electric propulsion. A common feature of the different aeronautical applications is the important safety need and the absence of catastrophic events linked to the use of such batteries, which are known for their high power density but also for their risk of thermal runaway that can lead to uncontrolled physical phenomena on board.
The phenomenon of thermal runaway is globally understood from the physical point of view but very difficult to model because it is a very exothermic phenomenon. We propose in this article to make a complete point on this subject and in particular, to approach the modeling of the safety of the batteries applied to the future aircraft and the phenomena of thermal runaway.

Introduction

The need for batteries is essential both for the more electric aircraft (MEA) and for future electric or hybrid-electric propulsion platforms.
In the case of MEA, batteries are currently used for a limited number of functions, such as starting the APU, on-board electrical backup functions or electrifying certain functions such as emergency braking. For the moment, the batteries used are mainly low-voltage batteries (28V) and there are very few cases of high-voltage batteries being used today, mainly in the military field. Replacing NiCd technology and mainly coming from the automotive industry, Lithium-ion technology, which is much more energetic, appeared for the first time on a commercial aircraft with the Boeing Dreamliner (batteries supplied by Thales Electrical Systems). The main advantage of using this technology is its power density, and for mission profiles such as those of the Dreamliner, Li-Ion technology is much better suited and allows for an overall reduction in the weight of cells carried on board the aircraft.
In order to optimize the mass, it is in our interest to select the cells with the most energetic chemistry, but the risk of thermal runaway is then even higher. It is therefore necessary to find the right compromise between the mass and the controlled risk of thermal runaway.
This last point requires a certain number of additional devices to limit the effects of thermal runaway of a cell and its propagation to the other elements of the battery, which can be very penalizing from the point of view of the mass and thus make lose the advantage specific to the Li-ion technology.
Many parameters are involved in the thermal runaway phenomenon, such as the nature of the chemical elements, the cell size, the number of cells and their relative arrangement within the battery pack, and the elements that allow the energy released to be either evacuated or absorbed.
Very little work has been done so far to model this phenomenon of thermal runaway.
It is the purpose of this article to review this phenomenon under several aspects such as the understanding of existing Standards, general approach to battery safety and modelling of the thermal runaway propagation phenomenon.

Understanding of aeronautical standards

Recently published [ref 1] the D03111 rev A standard specifies the test methods for aeronautical batteries and the criteria for battery evaluation. We will try to emphasize the hard points to handle in priority as well as the interpretations of the standard, in particular on the phenomena of propagation from a source cell to the other cells.

General approach to battery safety

We will discuss the actual modeling of thermal runaway propagation as a design aid. In this context, the modelisation approach has to be versatile, and adaptative, in order to adapt rapidly to different studied concept in the design phase. This flexibility can be achieved thanks to a modular approach. The simulation platform should also give the possibility to vary parameters in order to make first optimizations.

Modeling of the thermal runaway propagation phenomenon

The following points will be particularly addressed:

- Multi-OD modeling

- Presentation of high pressure closed vessel for thermal runaway energy evaluation with small cylindrical cells
- Contribution of finite element modeling

Multi-OD modelling

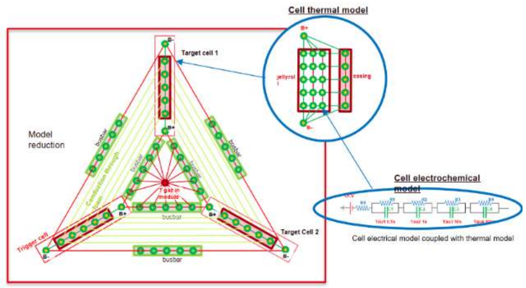

Fig 1 - Example of module with 4 cells

A modular simulation plateform is developped, based on matlab simulink. Multiphysics models (thermal, electrical...) are stored in libraries and are used for different studies along pack design process (performance studies, thermal runaway propagation...).

An hybrid apporaoch is developped combining :
- Multi-dimensional thermal models :
  - 0D (cell terminals, T° of gas medium)
  - 1D (bus bars, cell casing)
  - 2D (cell jellyrolls)
- A connecton of these blocs through a lumped approach (or multi 0D), through thermal conductance eventually obtained from FEM calculation (thermal conductance through insulation foam)
- Empirical circuit equivalent models representing electrochemistry, useful in order to take into account eventual short circuits

All the different blocs allow mutli-instantiation, giving the possibility to vary easily the number of cells.

The main objective of the thermal runaway multi-OD modelisation is to evaluate heat transferred from a trigger cell to the target cells and then their temperature evolutions. The goal is to avoid propagation when a first cell goes in thermal runaway in a module.

Closed cylindrical pressure vessel for thermal runaway energy evaluation

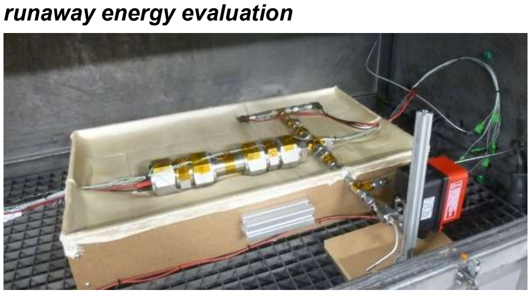

Fig 2 - Closed vessel equipped with pressure and thermal sensors

A closed pressure vessel calorimeter is used, allowing the evaluation of thermal runaway energy release as well as pressure evolution and gases composition. The thermal runaway of Li-ion cells is forced by a controlled temperature rise (6°C/min as defined in DO311A). The cell temperature, calorimeter temperature and pressure build-up evolutions are recorded during and after runaway. This allow evaluating precisely thermal runaway temperature threshold, gas volume exhausted and thermal runaway energy. This kind of test gives important data for modelisation activities detailed previously [ref 2].

Contribution of finite element modelling

CFD and FEM simulation are also realized and give reference results on which the multi 0D platform can rely. CFD simulation, with particle tracking gives heat exchange coefficients and gas temperature, whereas FEM heat conduction simulation gives thermal conductances between each cell pairs.

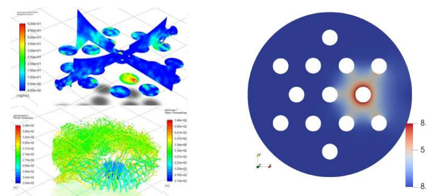

Fig 3 - Example CFD and FEM calculation

Conclusion

Modelling is an essential tool for guiding the design of battery modules, in particular to avoid propagation phenomena in the event of thermal runaway.

Even if today, a detailed understanding of all the physical phenomena related to thermal runaway is not yet acquired, modelling allows to simply carry out parameterized simulations and to give orientations for the design choices (distance between cells, insulation, impact of the bus-bar dimensioning, ...).

The main questions still open for the optimization of the models remain the precise evaluation of the gas versus particle ratio, the temporal evolution of pressures at any point in space, etc.

These questions are now being addressed by new research activities.

References

1 DO 311 rev A

2 William Q. Walker and al, Decoupling of heat generated from ejected and non-ejected contents of18650-format lithium-ion cells using statistical methods, Journal of power sources 415, 2019,207-218