Abstract

In the continuous aim to reduce the amount of minor actinides (MA) from the spent fuel of Light Water Reactors (LWR) and therefore reduce its radiotoxicity (radioactive toxicity), new nuclear fuel concepts have been developed. Sphere-Pac (SP) fuel gives the opportunity to reintroduce the MA in a fuel matrix and to burn them in a fast reactor, which facilitates a multi-cycle because of its breeding feature, or in a subcritical fast system, i.e. an Accelerator Driven System (ADS) where its sub-criticality allows higher MA contents than a normal fast reactor reducing efficiently the radiotoxicity in one step.

SP fuel is produced from the base solution (already containing all the elements) by internal gelation, which guarantees a good material homogeneity and a lower contamination risk compared to the classical pellet fabrication, avoiding presses and grinding machines. The internal gelation is an aqueous chemical reaction occurring when the solution is heated up to $80 \pm 5°C$. When performing the internal gelation process with electromagnetic heating, some advantages appear with respect to the traditionally heating through conduction by contact of the sample with hot silicon oil: the recycling step of the oil and the organic solvents necessary to clean the particles from oil are avoided. In the Microwave Internal Gelation (MIG) unit, the microwaves represent a much simpler and safer alternative: the contactless volumetric heating facilitates the remote production of the fuel in hot cells and furthermore reduces the contaminated liquid waste.

The fuel related project called Platform for Innovative Nuclear FuEls (PINE), in which this thesis is embedded, aims for the production of SP-fuel by MIG. In the MIG system, the heating time is very short (in the order of tens of milliseconds), therefore the microwave heating parameters have to be optimized and a good knowledge of the interaction between the microwaves and the samples must be achieved.

In the first part of this dissertation a finite difference time domain (FDTD) thermal model capable to determine over each instant about the thermal behaviour of a definite point inside a material during heat processing is investigated. A detailed overview of the most relevant parameters on the model including the boundary conditions (e.g. convection) is presented. Furthermore, the model is analytically implemented and validated with different techniques: a theoretical based physically validation, a partial differential equations (PDEtools) based validation and a validation with examples from the literature.

Secondly, possible microwave cavity designs for MIG are researched. The cavities (selection of modes, resonant frequency, Q-factor, etc.) and its subsequent characterization for the coupling of energy are explained. Furthermore, the power transfer mechanisms of the cavities are explained using the perturbation method to analyse the losses when a dielectric sample is placed inside a cavity. The developed power transfer model delivers the microwave heat generation rate which is applied to the FDTD thermal model mentioned in the previous paragraph. The analytical results provide a positive impression about the feasibility of producing gelated spheres by MIG.

Next, the main parameters dealing with the heating of a material by microwaves are introduced. A new procedure that enables the measurement of dielectric properties of aqueous droplets freely falling through a microwave cavity is developed. The experimental setup is presented and several experiments prove its feasibility. The measured dielectric properties are afterwards included in the perturbation and thermal models with the main intention of determining the absorbed power by the material in form of drops and the reached temperature.

In the last part the MIG system for the laboratory practice of the high frequency heating applied to the PINE project is implemented. Each device is characterized for a power study precedent to the MIG system assembly, avoiding then failures when putting the system into operation. In addition, the experimental techniques and the results are reported. Successful production of gelated spheres shows the favourable usage of microwave for the production of SP-fuel by internal gelation.

Keywords: Microwave Internal Gelation, Sphere-Pac Fuel, Resonant Cavities, Resonant Frequency, Q-factor, Dielectric Properties, Perturbation Method.